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CONTROLES ESTRUTURAIS DO DEPÓSITO DE ZINCO E CHUMBO DE BONSUCESSO, GRUPO VAZANTE, BRASIL

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Dissertação de Mestrado apresentada ao Instituto de Geociências e Ciências Exatas do Câmpus de Rio Claro, da Universidade Estadual Paulista "Júlio de Mesquita Filho", como parte dos requisitos para obtenção do título de Mestre em Geociências e Meio Ambiente.

Orientador: George Luiz Luvizotto

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“Say not 'This is the truth' but ' So it seems to me to be as I now see the things I think I see.' ”
David Love quoting some German inscription above some door
From Rising From The Plains by John McPhee

“You can't do geology in a hurry”
David Love in Rising From The Plains by John McPhee

Para Cida, Edinho e Lana

RESUMO

O recém-descoberto depósito sulfetado de zinco (Zn) e chumbo (Pb) de Bonsucesso está hospedado em rochas carbonáticas do Grupo Vazante em Paracatu, noroeste de do Estado de Minas Gerais, Brasil. Embora a idade do Grupo Vazante ainda seja matéria de debate, há ao menos um consenso de que este está posicionado na transição do Mesoproterozoico para o Neoproterozoico. Desenvolvida sobre a margem passiva da Paleoplaca São Francisco após a quebra de Rodínia, esta unidade é uma sequência sedimentar de primeira ordem. Este trabalho concentrou-se na avaliação dos controles estruturais do depósito de Zn e Pb de Bonsucesso e buscou entender a relação da mineralização com as estruturas e as rochas encaixantes. O Grupo Vazante foi afetado pela tectônica “thin-skinned” da zona de “foreland” do Orógeno Brasília e empurrado sobre a Paleoplaca São Francisco. Este longo processo orogênico foi o gatilho tectônico das várias mineralizações hospedadas nas rochas do Grupo Vazante. A mineralização de Bonsucesso é controlada por uma zona de falha de alto ângulo. Esta estruturação indica que a zona de falha aumentou a permeabilidade local e serviu como conduto para os fluidos mineralizantes.

Palavras-chave: zinco, geologia estrutural, MVT, Faixa Brasília, Formação Morro do Calcário

ABSTRACT

Recently discovered zinc (Zn) and lead (Pb) sulfide Bonsucesso deposit is hosted in carbonate rocks of Vazante Group, northwest of Minas Gerais State, Brazil. Although, the Vazante Group age is still a matter of debate, there is a general agreement that it is positioned in the transition of the Mesoproterozoic to the Neoproterozoic time. Developed over a passive margin of São Francisco Paleoplate after Rodinia break-up, this unit is a first-order sedimentary sequence. This work was focused on the assessment of the structural controls of Zn-Pb Bonsucesso deposit and evaluated the relationship between the mineralization, structures and host rocks. Vazante Group was affected by the thin-skinned tectonics of the foreland zone of Brasília Orogen and thrusted over São Francisco Paleoplate. This long orogenic process was the tectonic trigger of Zn-Pb mineralization hosted in Vazante Group rocks. Bonsucesso mineralization is controlled by a high-angle fault zone. This setting indicates that fault zone increased local permeability and acted as conduit for mineralizing fluids.

Keywords: zinc, structural geology, MVT, Brasília Belt, Morro do Calcário formation

Sumário

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CAPÍTULO 1

1.1. Introdução

O recém-descoberto depósito de zinco (Zn) e chumbo (Pb) de Bonsucesso está hospedado em rochas carbonáticas do Grupo Vazante em Paracatu, noroeste de Minas Gerais (Figura 1). Embora a idade do Grupo Vazante ainda seja matéria de debate, há ao menos um consenso de que esteja posicionado na transição do Mesoproterozoico para o Neoproterozoico (DARDENNE, 2000; MISI et al., 2014). Desenvolvida sobre a margem passiva da Paleoplaca São Francisco após a quebra de Rodínia, esta unidade é uma sequência sedimentar de primeira ordem (MARTINS-NETO, 2009; ALKMIM et al., 2001) com metamorfismo muito baixo (VALERIANO et al., 2004, VALERIANO et al., 2008; CARVALHO et al., 2016). Esta megassequência é correlacionável com outra unidade de mesma ordem depositada na margem oposta do cráton, o Grupo Macaúbas (ALKMIM; MARTINS NETO, 2012; REIS; ALKIMIN, 2015). As rochas do Grupo Vazante foram afetadas pela tectônica "*thin-skinned*" da zona de "*foreland*" do Orógeno Brasília e empurradas sobre a Paleoplaca São Francisco. Este longo processo orogênico foi o gatilho tectônico das várias mineralizações de Zn-Pb hospedadas nas rochas do Grupo Vazante. Junto com os conhecidos depósitos de Morro Agudo, Vazante, Ambrósia e Fagundes, esta nova descoberta integra o maior distrito produtor de Zn no Brasil. O novo corpo de minério é resultado da pesquisa mineral conduzida pela Nexa Resources, antiga Votorantim Metais, no "*trend*" enriquecido em metais (Zn e Pb) e comumente chamado pelos geólogos de exploração como Faixa Vazante.

A relevância de sistemas de falhas como estruturas hospedeiras de mineralizações hidrotermais é conhecida há muito tempo (COX, 2005; SIBSON, 1996; NEWHOUSE, 1942; MCKINSTRY, 1948). E a associação entre regimes tectônicos extensivos e mineralizações tem sido estabelecida em muitos depósitos minerais hidrotermais (SIBSON, 1996, 2000). Entretanto, depósitos de metais-base associados em sua gênese com falhas contracionais também tem sido reportados, embora pouco estudados (ZHANG et al., 2017; HOU; ZHANG, 2015; GHAZBAN et al., 1994; LIAGHAT et al., 2000).

O estudo teve como objetivo caracterizar os controles estruturais do minério na escala de depósito e formular hipóteses para a sua formação. Adicionalmente, pretendeu-se dar significado às estruturas controladoras e modificadoras em seu contexto tectônico regional.

Feitas as correlações, estas informações podem ser úteis para a exploração de novos depósitos na região.

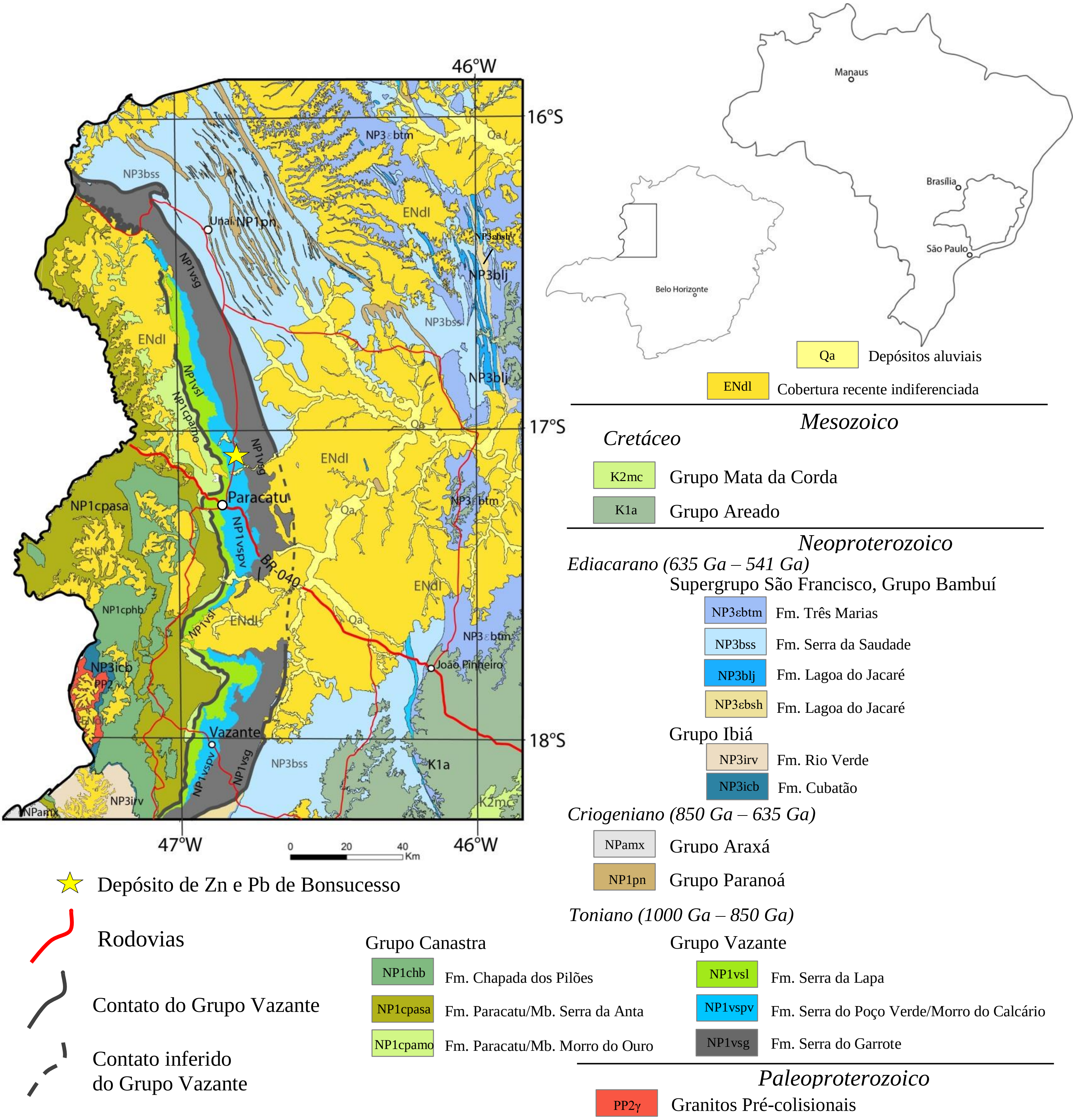

Figura 1: Mapa geológico do noroeste de Minas Gerais com a localização do depósito de Bonsucesso. O Grupo Vazante (destacado por linhas cinza escuro) está situado na borda do Cráton do São Francisco. Porém, o embasamento do cráton não está exposto. O Grupo Vazante (Esteniano-Toniano) faz contato tectônico com unidades do Grupo Bambuí (unidade Ediacarana) também depositadas na margem do cráton (Modificado de CPRM, 2003).

1.2. Métodos

Os dados estruturais foram coletados em testemunhos orientados perfurados no depósito de Bonsucesso. Os furos inclinados das primeiras campanhas de sondagem no depósito foram orientados com arpão. Esta técnica de orientação é antiga e muito simples, consiste de um arpão de aço com a ponta afiada que é lançado dentro das hastes após a retirada do barrilhete. O arpão faz uma marca na parte inferior da superfície do testemunho que ainda não foi retirado, então a marcação é recuperada após a retirada do próximo intervalo perfurado (ZIMMER, 1963; MARJORIBANKS, 2010). Contudo, problemas com o arpão podem surgir quando a rocha é muito dura ou muito frágil, pois tanto pode o arpão pular e produzir marcas de difícil interpretação (rocha muito dura) como pode fragmentar o testemunho com o impacto sobre rochas frágeis (MARJORIBANKS, 2010). Porém, a maioria dos furos foram orientados com o instrumento ACT III da Reflex®.

Este método baseado em acelerômetros (medição da força contínua da gravidade), o dispositivo é acoplado ao barrilhete e a orientação é feita durante a sondagem. Após a retirada dos testemunhos, as marcações da base (ou topo) do testemunho são feitas com o auxílio de um nível de bolha. Os fragmentos de testemunhos são então dispostos sobre uma canaleta para que o intervalo perfurado possa ser reconstituído em toda sua extensão, embora nem sempre isto seja possível devido à fragmentação das rochas. Depois de reconstituídos, a linha de base é traçada.

Três técnicas foram utilizadas para coletar as medidas estruturais (Figura 2): (i) uso de lança-foguetes e bússola (esta técnica é prática, permite a coleta de todos os tipos de lineações e planos, mas não é adequada para materiais magnéticos); (ii) consiste na medição dos ângulos internos dos testemunhos (alfa, beta e gama), sendo que ângulos posteriormente foram transformados em atitudes (*strike, dip, dip direction, trend, plunge*) com a utilização de programa específico (Leapfrog Geo®) e (iii) the método vSET™, outra técnica baseada em relações geométricas e mais adequada para medida de estruturas lineares.

Como as medidas estruturais tem um caráter muito mais qualitativo do que quantitativo, o número de medidas coletadas variou de acordo com a representatividade e variabilidade das estruturas e também da disponibilidade de intervalos orientados. Atitudes constantes por muitos metros de testemunho, como o acamamento das rochas, requerem algumas poucas medidas para que possam ser bem representadas, ao passo que intervalos com uma variabilidade muito grande ou com mineralização merecem mais atenção e, por consequência, mais medidas.

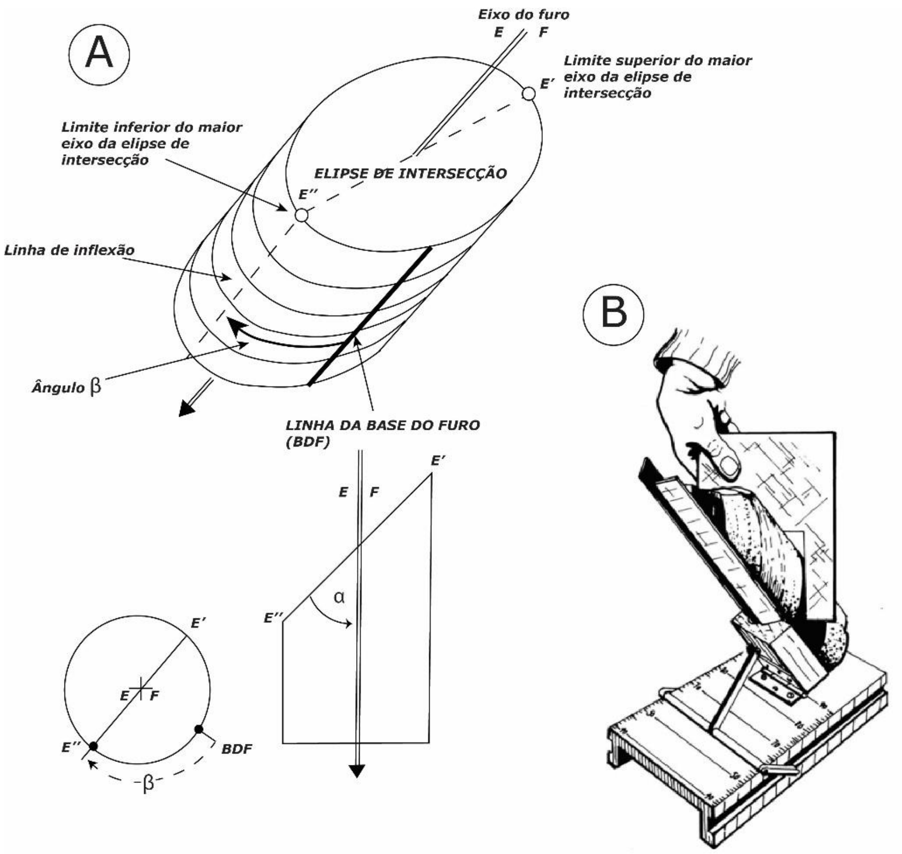

Figura 2: A. Representação dos ângulos alfa (α) e beta (β) usados para definir as atitudes das estruturas em sondagem orientada. B. Exemplo de coleta de estrutura planar com auxílio de uma extensão em um orientador de furos, popularmente conhecido como lança-foguetes (modificado de MARJORIBANKS, 2010).

Para reconstruir a geometria do depósito foi utilizado o programa de modelamento geológico 3D Leapfrog Geo®. Os dados litológicos foram inseridos no programa como classes e texto, enquanto que as medidas estruturais foram inseridas como vetores. Onde não não havia informação de sondagem, a espessura e as atitudes das camadas foram modeladas implicitamente.

Os mapas composicionais foram gerados no Laboratório de Microssonda Eletrônica do Departamento de Petrologia e Metalogenia da Unesp, utilizado equipamento da marca JEOL, modelo JXA8230, equipado com 5 detectores WDS, detector EDS do tipo SSD, detectores de elétrons secundários (SEI) e elétrons retroespalhados (BSE). Para a geração dos mapas quantitativos de fases minerais foi utilizado o programa XMapTools (LANARI et al., 2014; LANARI et al., 2019).

1.3. Estrutura da dissertação

A dissertação está dividida em três capítulos. O capítulo 1 é uma breve introdução do problema e também apresenta o objetivo da pesquisa. O capítulo 2 é um manuscrito a ser enviado a revista *Ore Geology Reviews.* O foco do artigo é a história deformacional do depósito e a caracterização dos controles estruturais da mineralização. O capítulo 3 contém conclusões gerais do estudo.

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CAPÍTULO 2

STRUCTURAL CONTROLS ON THE BONSUCESSO ZINC-LEAD DEPOSIT, VAZANTE GROUP, BRAZIL

Um manuscrito a ser submetido a Ore Geology Reviews

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1. Introduction

The Bonsucesso Zn-Pb sulfide deposit is a recent discovery hosted in carbonate rocks of the Vazante Group in Paracatu, Northwest of Minas Gerais, Brazil. Although the Vazante Group age is still a matter of debate, there is a general agreement that this sedimentary sequence was at least deposited at about 1000 Ma in the transition of the Mesoproterozoic to the Neoproterozoic time (DARDENNE, 2000, MISI et al., 2014). Together with the known deposits of Vazante (total estimated resources of 60 Mt @ 20 %), Morro Agudo (total estimated resources of 20 Mt @ 5.0 % Zn and 1.75 % Pb), Ambrósia Sul (2.15 Mt @ 5.0% Zn and 0.16% Pb) and Fagundes (2.8 Mt @ 4.0 % and 0.3 Pb), this discovery is a part of Brazil's best-endowed district for Zn.

Geologic structures play a fundamental role in almost all types of mineral deposits. Thus, a better understanding of the structural architecture of the mineralization is a powerful guide to grade continuity and may reduce misinterpretations (COWAN, 2014).

The relevance of fault systems as host structures for hydrothermal mineralization has long been reported (COX, 2005; SIBSON, 1996; NEWHOUSE, 1942; MCKINSTRY, 1948).

And the relation of formation of fault-fracture networks and fluids redistribution in extensional and transtensional regimes plays a crucial role in the formation of many hydrothermal mineral deposits (SIBSON, 1996, 2000). Although, base-metal deposits related to contractional faults have also been reported and infilling of mineralization fracture–meshes coeval with compressive settings has been recognized (ZHANG et al., 2017; HOU; ZHANG, 2015; GHAZBAN et al., 1994; LIAGHAt et al., 2000).

At Bonsucesso deposit major fault-ruptures are related to the Brasiliano orogeny (ca 900 Ma - 600 Ma, PIMENTEL, 2016), the last compressive tectonic event that took place over the Vazante Group rocks and that gave origin to the Brasíia fold-and-thrust belt (ALMEIDA, 1981; DARDENNE, 2000; VALERIANO et al. 2004; VALERIANO et al., 2008).

In this paper, we describe the ore textures and the structures of this deposit in the context of the other Vazante Pb-Zn deposits. The goal of this study is to characterize the structural controls of the ore in deposit scale and formulate hypotheses about its forming process. Furthermore, a reasonable understanding of local controls may be of good use to target exploration for new orebodies in the district scale.

2. Methods

Detailed field mapping was difficulted because of the thick soil layer above the the Bonsucesso deposit. The 3D geological modelling software Leapfrog Geo® was used to build deposit’s geometry. Drillhole data integration was done inside the the software and lithological description was input as classes and text while structural measurements were input as vectors. Where drillhole data was absent true thickness of layers and surfaces dipping were fully implicitly modelled.

An electron microprobe JEOL, model JXA8230, equipped with 5 WDS detectors, EDS detector type SSD, secondary electrons detectors and back scattered electrons (BSE) was used to generate compositional maps. And for quantitative EPMA maps showing mineral variability the XMapTools software was used (LANARI et al., 2014; LANARI et al., 2019).

Structural measurements were collected from oriented drill core. First inclined drill holes were oriented with the core stub method. This technique consists of a steel spear with a sharp point lowered inside the rods to mark the position of gravity vector (i.e. to determine the bottom of hole) on the core stub after the extraction of a full core barrel (ZIMMER, 1963; MARJORIBANKS, 2010). However, most of drill holes were oriented using the core barrel method, which orients the drill hole at the moment when the lowest piece of core is griped by the lifter before breaking it free (MARJORIBANKS, 2010). The electronic device used was the Reflex ACT III. After the extraction of the core barrel, bottom (or top) of hole marks were made. Thus, broken drill core pieces were laid out over a channel to be as much reassembled as possible. After the reassembling, bottom lines were traced along the run with arrows pointing down-hole.

Three techniques were applied to measure structures: (1) the rocket launcher, which consisted of a wood set that replicates drill rig orientation at the coreshed and allows geologists to position oriented core samples as they were in situ and so collecting structures, (2) measurement of internal core angles (alpha, beta and gamma) later transformed by Leapfrog Geo® software or spreadsheet into real strike and dip or trend and plunge values already corrected by desurveying methods, and (3) the vSET™ method, another technique also based on geometrical relationships and more suitable to measurement of linear structures.

Since structural data has a more qualitative aspect than quantitative, the number of measurements varied according to representativeness and variability of the structures as suggested by MARJORIBANKS (2010).

3. Geological setting

The Bonsucesso deposit is located in the Paracatu region, northwest of Minas Gerais State, Central Brazil. Zinc-lead sulphide mineralization is hosted in rocks of the Vazante Group (Tonian period, ca 1000 Ma, CARVALHO et al., 2019) on the southeast sector of Brasíllia Belt.

The origin of this fold-and-thrust belt dates back to the São Francisco paleoplate Late Mesoproterozoic to Early Neoproterozoic rifting to full passive margin development (CATUNEANU et al. 2005; MARTINS-NETO, 2009). And it ends with thin-skinned tectonics as the São Francisco paleoplate subducted to the West during the assembly of West Gondwana (MARTINS-NETO 2009, ROMEIRO-SILVA; ZÁLAN, 2007).

Understanding of the Brasília Belt evolution has increased over the years and new geochronological data have helped to better constrain major tectonic compartments. Pimentel (2016) established four divisions from West to East (Figure 1): Goiás magmatic arc, syn-orogenic basins (fore-arc?) and metamorphic core, passive Margin (the supracrustal sequences of the fold-and-thrust belt primarily deposited over the São Francisco craton margin), and foreland basin (cratonic cover).

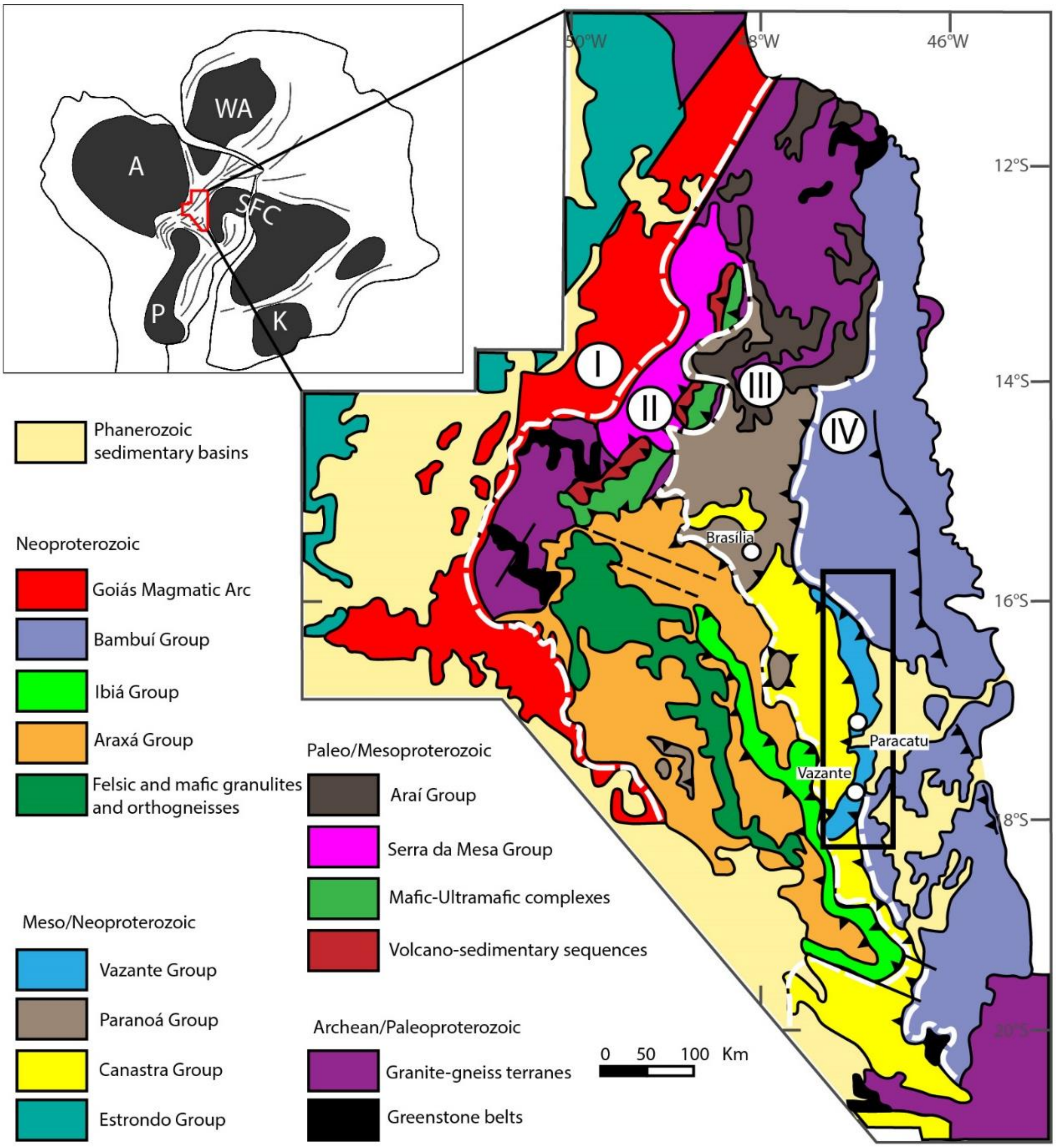


Figure 1: Generalized geological map of Brasília Belt showing units and tectonic compartments according to Pimentel (2016): I – Goiás magmatic Arc, II - Syn-orogenic basins (fore-arc?) and metamorphic core, III - Passive margin, and IV - Foreland basin. Vazante Group (outlined) is on the east of the Southern Brasília Belt. On the upper left corner, location of Brasília Belt in the West Gondwana (ca 550 Ma). Curved lines: Neoproterozoic Brasiliano/Pan-African orogens. Cratons: A –

Amazonian, SFC – São Francisco Congo, P – Rio de la Plata, WA – West Africa, K – Kalahari (ALKMIM et al., 2001).

The Vazante group extends N-S through nearly 250 km length with an average width of 30 km (Figure 2). To the West it is bounded by the Canastra group (similar age), and to the East by the Bambuí group (553-542 Ma, WARREN et al., 2014, PAULA-SANTOS; BABINSKI, 2018). Metamorphic conditions reached peak at low greenschist facies (MONTEIRO et al., 2006) with development of pervasive axial plane cleavage in general parallel to bedding and formation of crenulation cleavage related to isoclinal folding and later open folds, respectively (CARVALHO et al., 2016).

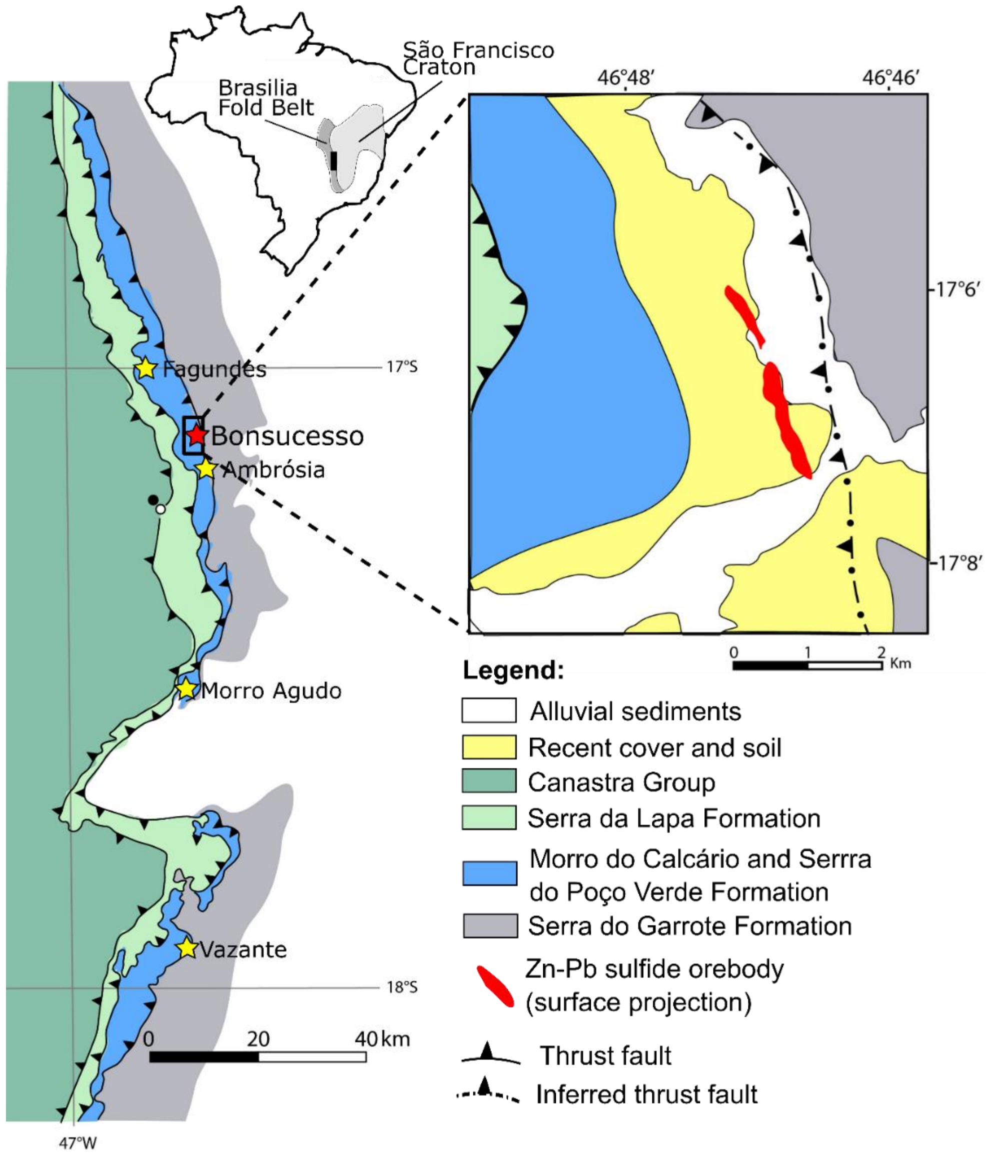


Figure 2: Map of Brazil showing the location of Brasilia Fold Belt and part of the Eastern Brasília Fold Belt with the location of the major Zn-Pb sulfide deposits (Morro Agudo, Ambrósia, Bonsucesso

and Fagundes) and Zn silicate deposit (Vazante). It is also showed the geological map of Bonsucesso deposit.

This unit constitutes a thick metasedimentary sequence originally deposited in shallow waters of the São Francisco paleoplate passive margin. It is divided into seven formations (Figure 3), from base to top: Santo Antônio do Bonito, Rocinha, Lagamar, Serra do Garrote, Serra do Poço Verde, Morro do Calcário and Serra da Lapa (DARDENNE et al., 1998; DARDENNE, 2000). The basal Santo Antônio do Bonito and Rocinha formations are composed of metapelitic units with phosphate concentrations (DARDENNE, 2000).

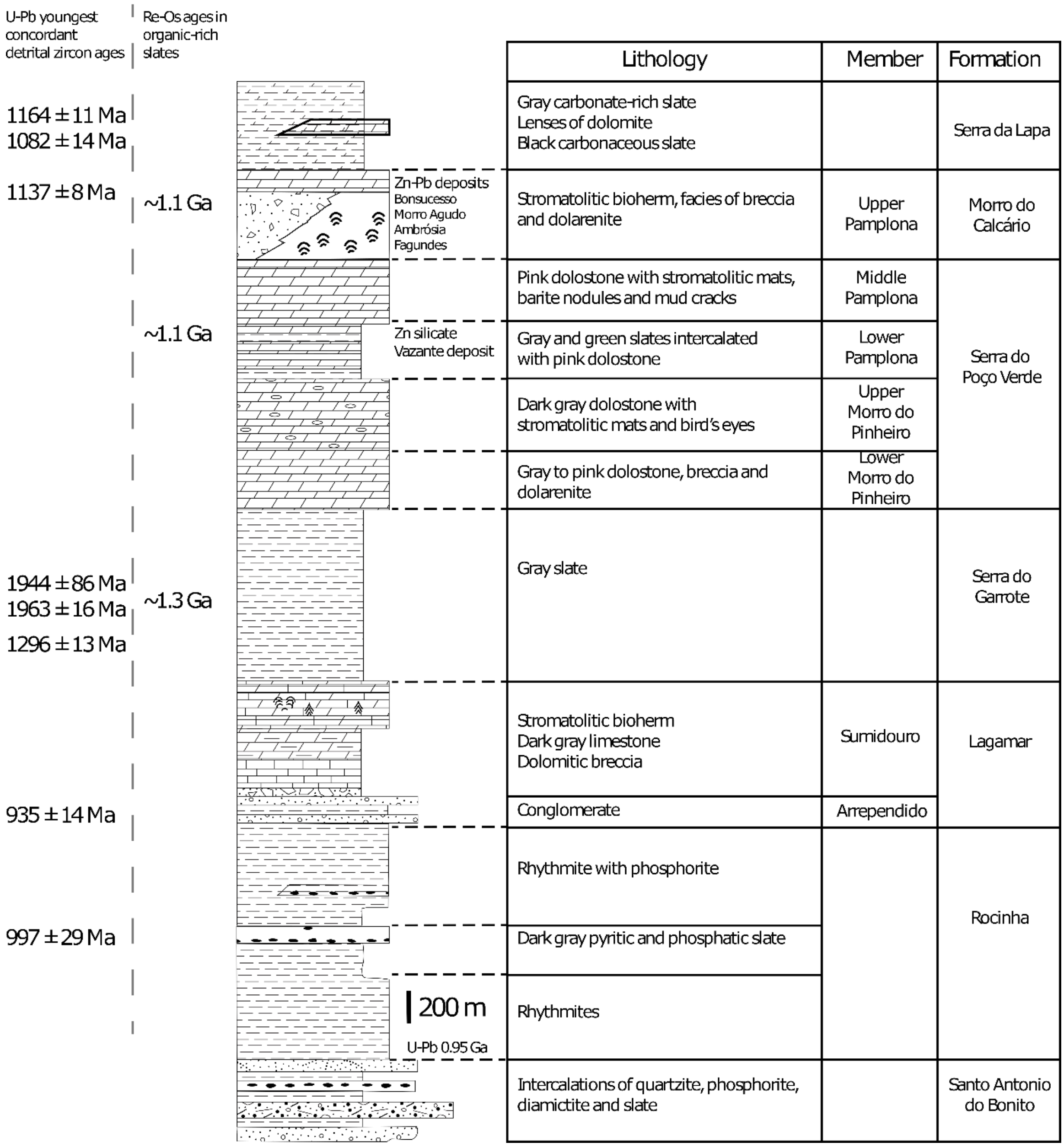


Figure 3: Lagamar thrust fault juxtaposed older sediments of Vazante group and younger sediments of Bambuí group. Original cross-section from Dardenne and Freitas-Silva (1999). Stratigraphic column

of Vazante group (after Dardenne, 2001). Bonsucesso Zn-Pb deposit is hosted in the same unit (Morro do Calcário) as Morro Agudo, Ambrosia and Fagundes deposits. U-Pb detrital zircon ages from Rodrigues et al. (2012); Re-Os ages from Geboy et al. (2013) and Azmy et al. (2008).

According to Dardenne et al. (1998) and Dardenne (2000), the Lagamar Formation represents a metapsamo-pelitic unit with basal metaconglomerates, dolomitic breccia, dark gray limestone and stromatolitic bioherm with columnar stromatolites of the *Conophyton* and *Jacutophyton* type The Serra do Garrote Formation represents a sequence of pyrite-bearing carbonaceous gray slate and quartzite layers The Serra do Poço Verde Formation is made of gray to pink algal-laminated dolomite, gray to green slates, sericite phyllite, dark gray dolomite with bird's-eyes, marls and pyrite-bearing carbonaceous shale. The Morro do Calcário Formation is composed of stromatolitic bioherm facies, intraformational breccias, dolarenite, and subordinate carbonaceous shale These two formations correspond to the dominantly dolomitic sequences that host the Zn–(Pb) deposits and can represent a continuously deposited dolomitic sequence. The dolomitic sequence is overlain by the Lapa Formation, with black rhythmic carbonaceous slate and phyllite (Serra do Velosinho Member) and sericite–chlorite phyllite, carbonate-bearing metasiltstone, dolomite and quartzite lenses (Serra da Lapa Member).

The area has been studied since the 1950's, but the Vazante group age is still an unresolved problem, mainly due to absence of absolute markers (e.g. volcanic layer) and to wide span in time provided by the fossil record (*Conophyton* stromatolite; 1.35 Ga to 0.95 Ga).

A Rb-Sr whole rock isochron for shales from Vazante Group yielded an age of 600 + 50 Ma (AMARAL; KAWASHITA, 1967), which could represent the last closing of the isotopic systems during the Brasiliano metamorphic event. Re-Os ages in organic-rich slates of the Vazante group (AZMY et al., 2008; GEBOY et al., 2013), and U-Pb ages of detrital zircons in quartzites distributed along the whole sequence (RODRIGUES et al., 2012) provided a Late Mesoproterozoic age for the top and an Early Neoproterozoic age for the basal units. Furthermore, these Late Mesoproterozoic ages agree with seismic, well and outcrop data that correlate the Vazante group with the Macaúbas group on East of São Francisco craton. Both units comprise first order sedimentary sequences developed over the São Francisco craton margins when supercontinent Rodinia broke up (MARTINS-NETO, 2009; ALKMIM; MARTINS-NETO 2012). Based on the new geochronological data and field relations, Misi et al. (2014) argued that the upper and older section (Lagamar to Serra da Lapa formations) was thrusted (Lagamar fault zone) over the younger lower section (Santo Antonio do Bonito and Rocinha formations). Misi et al. (2014) also suggested a connection of the lower section with the Bambuí group (Figure 3).

4. Geology of the Bonsucesso deposit

Geological characterization was focused on rocks and structures within the mineralized zone as exploration drilling has its search range constrained by it.

4.1. Lithologies and stratigraphy

Two lihostratigraphic units were identified at Bonsucesso deposit: (1) Serra do Garrote Formation and (2) Morro do Calcário formation. The hydrothermal dolomitic breccia containing the Bonsucesso orebodies is hosted in metapelite and carbonate rocks of the Morro do Calcário Formation (Figure 4). Rocks of Serra do Garrote formation were emplaced between Morro do Calcário unit by a reverse fault. The following lithological description is restricted to hangingwall and footwall rocks of the Bonsucesso fault-controlled deposit.

4.2. Soil

The Bonsucesso deposit lies under 30 meters thick allochthonous soil and recent sediment cover. Besides there is no compelling geochemical anomaly on the surface over the mineralized zone, it is important to highlight this feature because mineral exploration on areas with recent cover must be encouraged and many blind deposits may have been overlooked. On top, the soil cover has a distinctive 5 meters thick clay-rich layer enriched in magnetite, which consists of red and orange clay and quartz rich material mixed with clasts of dolostone and chert (ARAUJO, 2018). This soil coverage acts as a barrier, where conventional geochemical and geophysical techniques are not so useful for mineral exploration.

4.3. Serra do Garrote Formation

The Serra do Garrote Formation consists of black to grey carbonaceous phyllites (or slates?). Occurrence of 1 to 3-centimeters radial pyrite nodules and also fine layers of pyrite parallel to bedding are common. Near the fault zone, these rocks are brecciated and veining by calcite and quartz is strong.

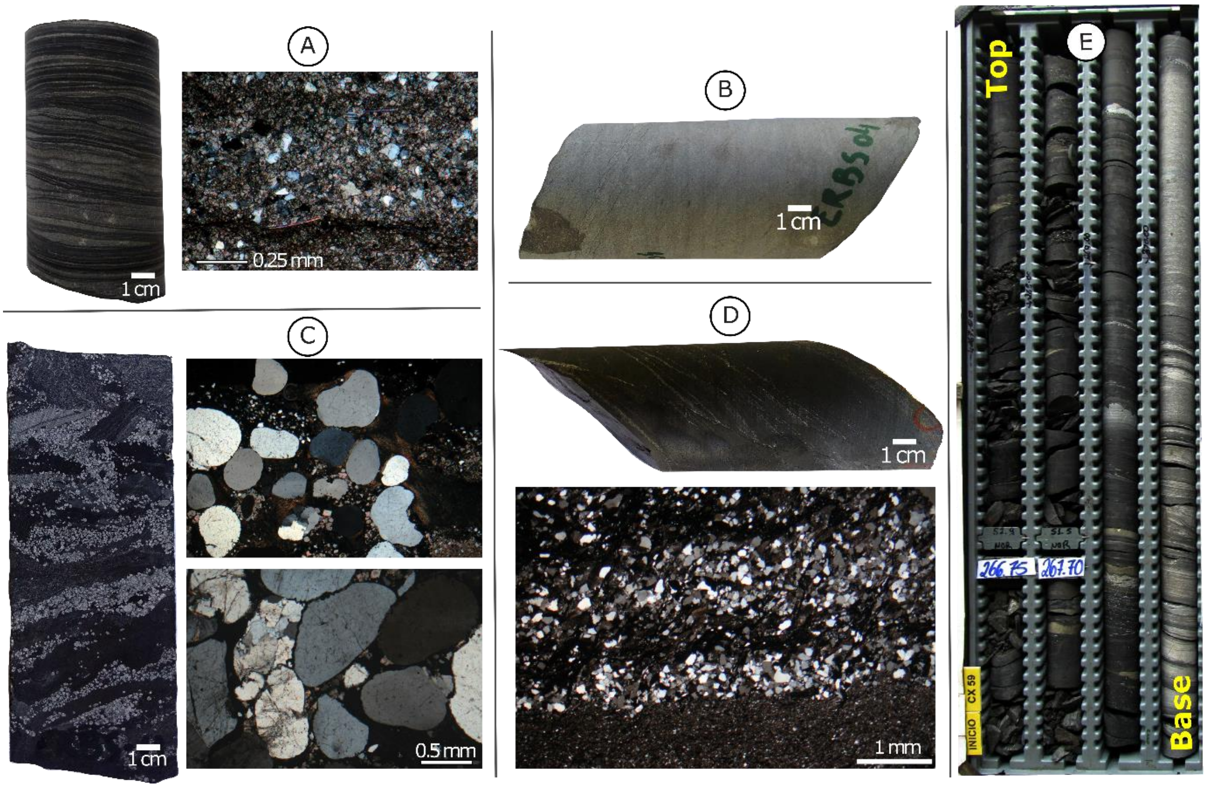


Figure 4: Lithotypes and textures of Bonsucesso deposit. A. Metamarl. Bedding marked by alternating mm to cm thick carbonate-rich layers and mica-rich layers. Note on thin section the presence of clasts of muscovite and quartz. Cross polarized light. B. Fine dolostone with discrete bedding. C. Diamictite. Core sample exhibits mixture of coarse clasts of carbonate rocks and well-rounded quartz sand in a fine black matrix. Thin section shows a heterogeneous origin for quartz sand, including lithic clasts and quartz with wavy extinction. Microcrystalline phosphate (P) also occurs in matrix as cement. D. Carbonaceous phyllite with bedding marked by quartz-rich layers and carbonaceous mica-rich layers (Serra do Garrote Formation).Cross polarized light. E. Transition of metamarl to black carbonaceous phyllite. These rocks occur interbedded within Morro do Calcário Formation.

4.4. Morro do Calcário Formation

A variety of dolomite rocks comprises both hangingwall and footwall blocks. Massive micritic dolostone, columnar stromatolitic dolostone, dolorudite with lamellar breccia, dolarenite, intraformational breccia, oolitic dolostone and laminated dolostone are the main lithotypes. Void-filling white dolomite occur as veins near damage zone and fault-core. Dark chert veins are also related to hydrothermally altered zones. Below the soil cover, weak acidic water flow has promoted strong dissolution of dolostone along bedding planes, joints, fractures and fault zones to form an intricate system of caves at shallower levels.

Within the dolomite unit there is a distinctive package of carbonate mudstone whose true thickness varies from 80 meters at south sector and gradually decreases to 40 meters at north sector. These rocks are interbedded thin carbonaceous mica-rich layers and micritic dolomite with minor terrigenous contribution (clasts of quartz and feldspar) occurring in hangingwall and footwall blocks. This rock is a mixture of siliciclastic and carbonate material. The carbonate layers are composed of fine angular clasts in matrix and gravels of dolomitic mudstone and dolostone, whereas the terrigenous component contains well-rounded coarse quartz sand, angular fine quartz clasts, rare fine feldspar clasts, lithic clasts and carbonaceous mica-rich matrix. Phosphate occurs as fine agglomerate of cryptocrystalline apatite in matrix. This rock forms very restricted beds frequently separated by erosion surfaces at the bottom and it is generally overlaid by finer-grained sequence enriched in organic matter. Given these very particular features, this layer is an excellent structural and stratigraphic marker and was used to balance cross sections and the 3D model.

4.5. Hydrothermal dolomitic breccia – Bonsucesso Zn-Pb mineralization

The zinc and lead orebodies of the Bonsucesso deposit are hosted in a hydrothermal dolomitic breccia. There are two mineralized zones. The upper zone occurs in the hangingwall along the fault strike and dip, below the carbonate mudstone layer and above the Serra do Garrote carbonaceous phylite and its basal contact with the latter has little to none shearing. In the footwall, the mineralized zone also extends along the fault surface, above the carbonate mudstone package and below the Serra do Garrote phyllite, and its contact with the latter exhibits strong shearing (Figure 5).

The host rock is a hydrothermally brecciated dolostone with intense veining by white coarse dolomite and sulfides. The deposit strike length is around 4000 meters, but brownfield exploration programs have demonstrated a potential for extension. Breccia zone thickness varies through the strike and mineralized zones within it may vary as well as the faulting process is a major permeability control and deformation is heterogeneous. In general, the mineralized zone is hosted in a 50 meters brecciated dolomite whose extensions controlled by faults. Based on the texture, two prevailing mineralization types have been described: i) breccia with angular dolostone-clasts surrounded by sphalerite and galena and gangue minerals (pyrite, white dolomite and quartz), and ii) veins of sphalerite and galena. The mineralogy of the Bonsucesso is relatively simple. Mineralization is comprised of sphalerite and galena and gangue minerals are pyrite and white dolomite with scattered punctuations of pyrobitumen. Sphalerite color ranges from grey to dark grey and pale-yellow to amber. Former represents the major Zn sulfide component of the deposit and later is often related with late and coarser sphalerite mineralization (Figure 6).

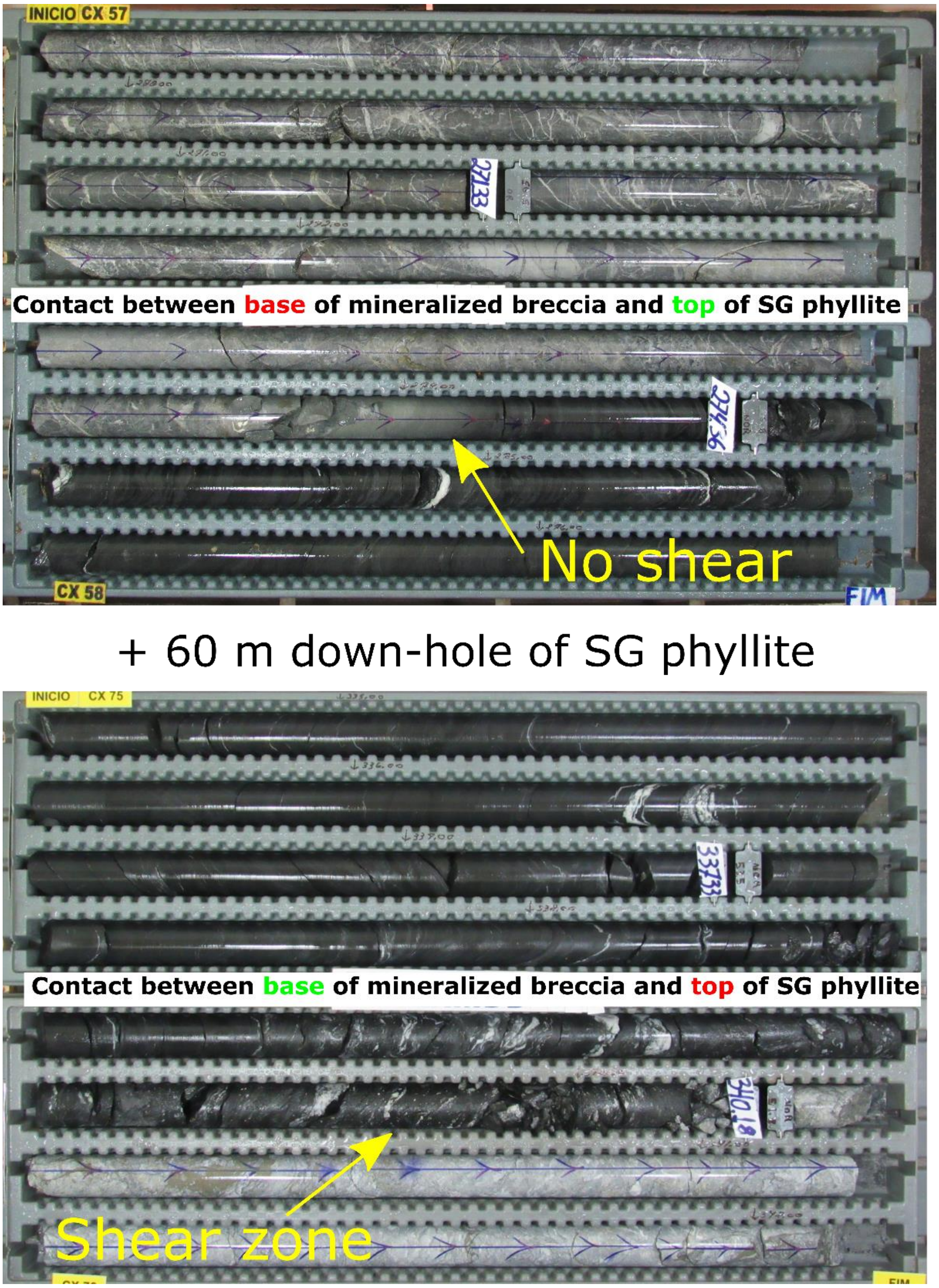


Figure 5: The relationship between the mineralized zones in the hangingwall with no shearing and the footwall with strong shearing along the fault strike and dip.

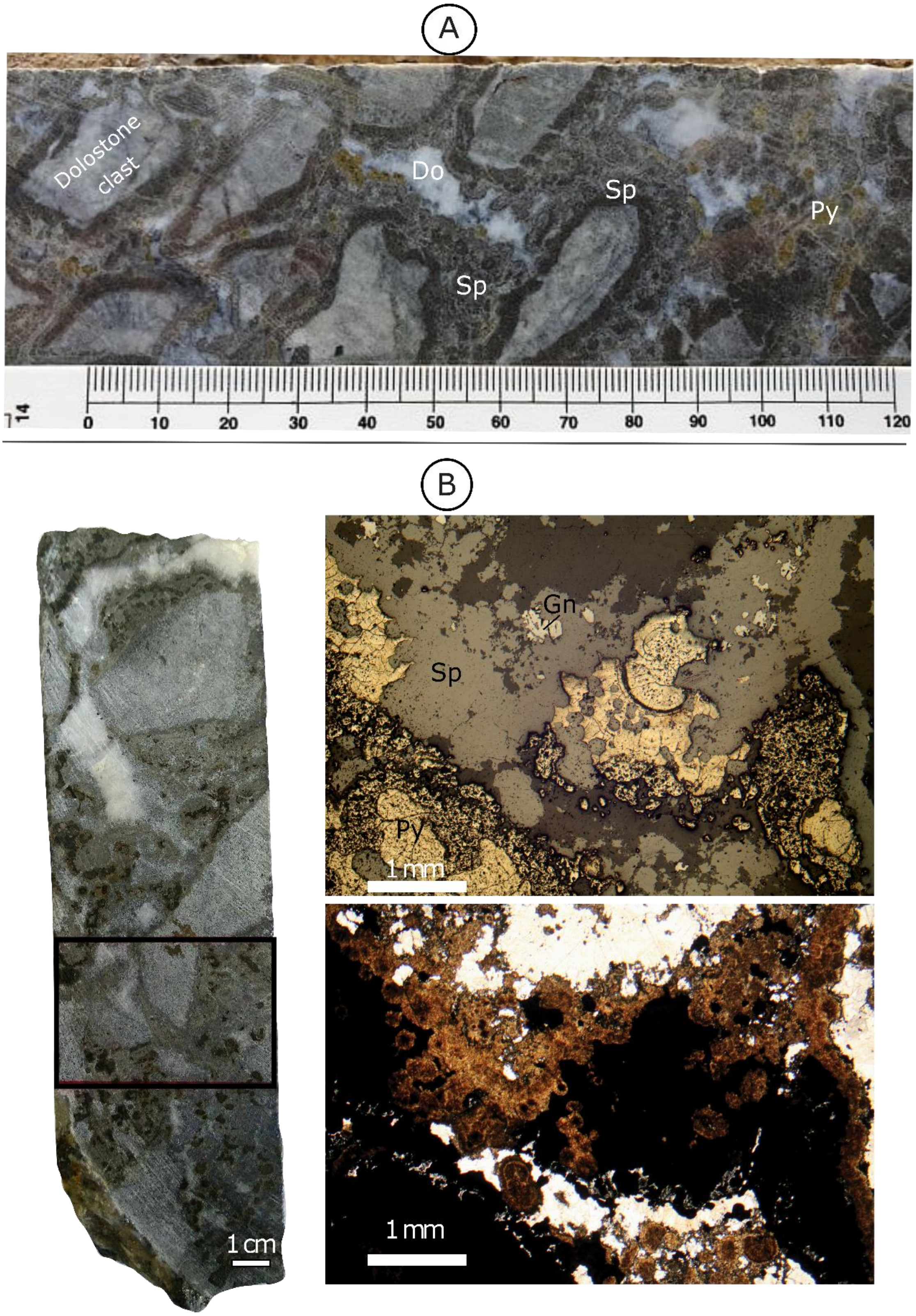


Figure 6: A. Hydrothermal dolomitic breccia almost entirely cemented by gray and yellow colloform sphalerite (Sp). B. Sulphide and gangue-minerals (mainly dolomite – Do) filling of inter-fragment open spaces in dolomitic breccia. Thin section (reflected light at top; transmitted light at bottom): Colloform sphalerite replaced colloform pyrite (Py).

5. Ore mineralogy

Colloform pyrite was constantly observed as a sulfide phase replaced by masses of sphalerite and galena. Mineralization by veining is marked by injection of sphalerite and galena at high angles, often in extensional veins. A well-formed pyrite and destruction of sulfide phases by carbonate minerals and quartz is also common (Figure 7).

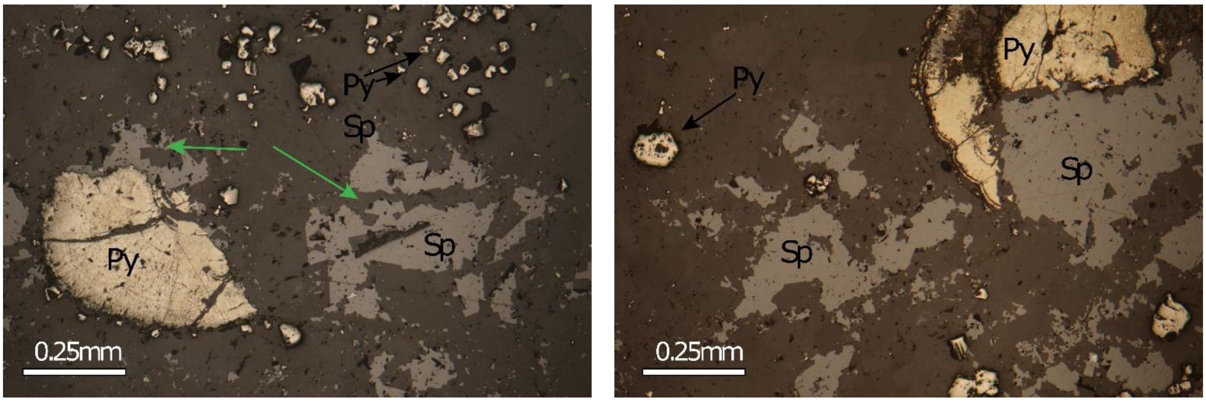


Figure 7: At left, sphalerite replaced colloform pyrite and later same sphalerite was substituted by carbonate mineral (note rhombohedral crystal indicated by green arrows). At right, other example of sphalerite replacing early phase of colloform pyrite. Both thin sections a contains a late phase of euhedral pyrite.

Monteiro (2002) documented the existence of oil inclusions in sulfide phases related to mineralization in the Vazante Belt. At Bonsucesso deposit, the occurrence of pyrobitumen among hydrothermal mineral phases is very common. Relationship of pyrobitumen with sphalerite is clearer at microscopic scale where sphalerite-bearing veins show oil residues in direct contact with Zn sulfide. At mesoscale is also possible to see specks and needle-like pyrobitumen among gangue minerals (Figure 8).

6. Structures

6.1. Structural framework

Because São Francisco paleoplate subducted underneath Brasília orogen, the sedimentary rocks of the Vazante group were affected by thin-skinned tectonics in the foreland. Seismic lines clearly exhibit a deformation of shallow allochthonous thrust sheets of the Vazante, Canastra and Bambuí groups. At the seismic sections's western edge (Figure 9), the sheets are shortened and lie over the décollement zone, which marks the unconformity that separates them from the Paranoá/Macaúbas megasequence (ROMEIRO-SILVA; ZÁLAN, 2007).

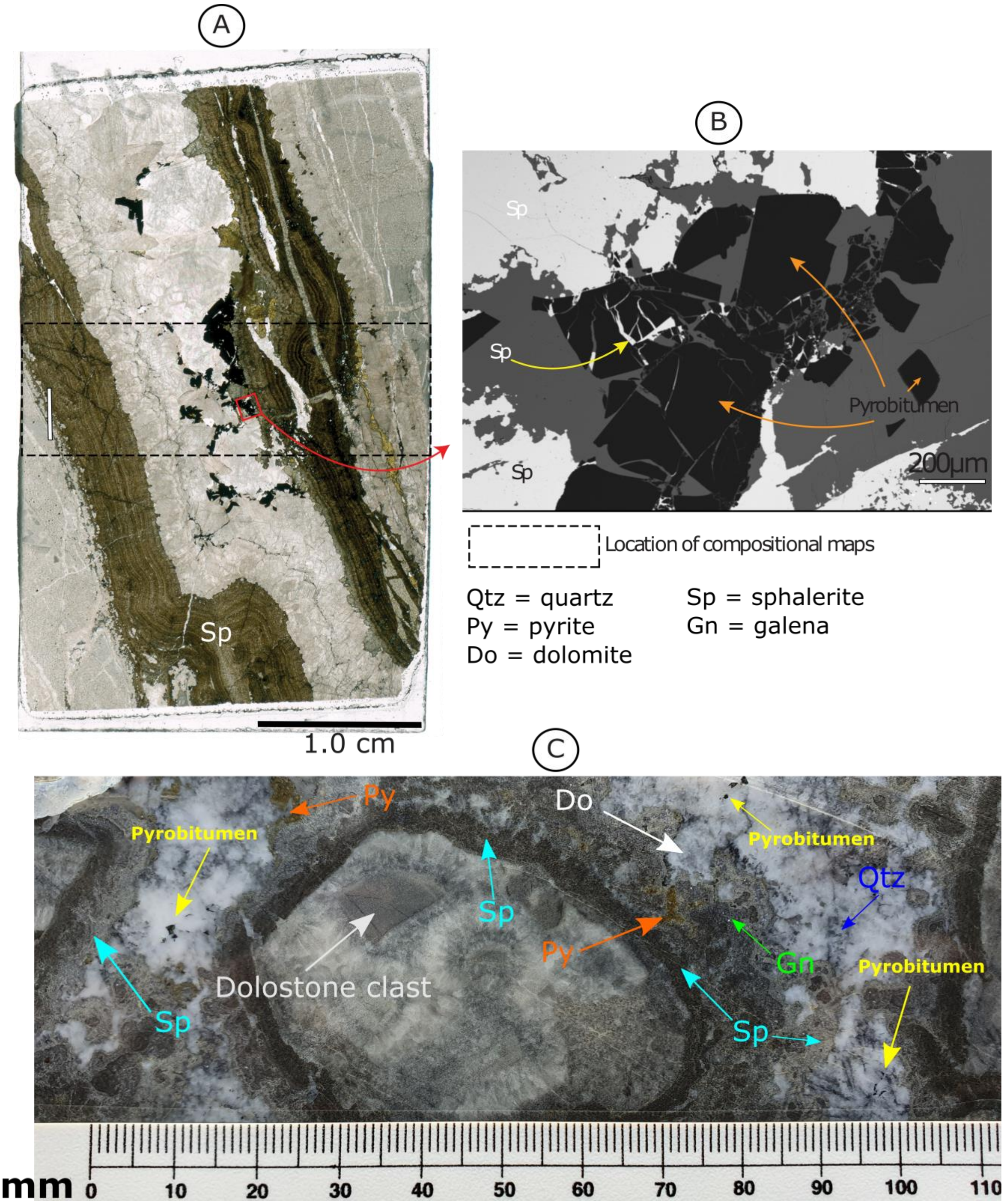


Figure 8: A. Sp-bearing extensional vein. B. EDS image showing pyrobitumen in contact with Sp Red arrow indicates location of EDS image. C. Mineralized breccia texture: Colloform Sp and Gn and also gangue minerals filling space between clasts of dolostone.

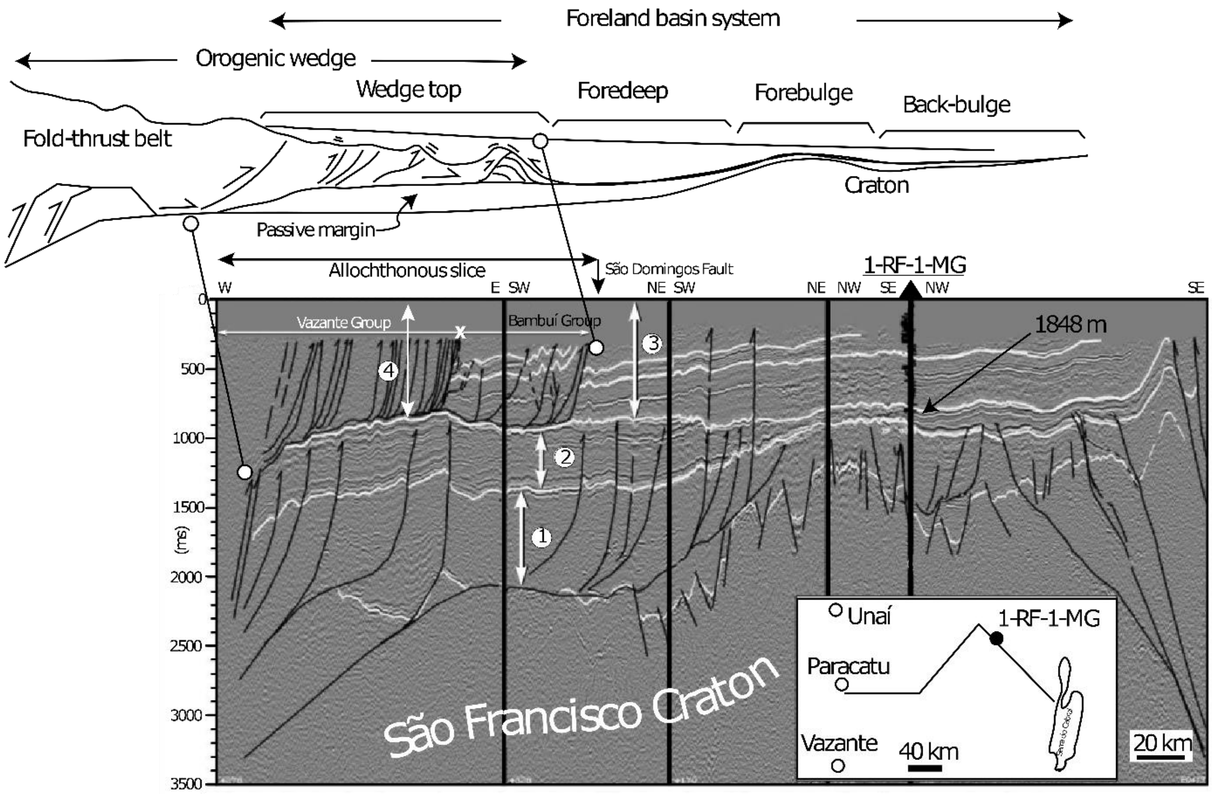


Figure 9: Schematic cross-section depicting a foreland basin system (modified from DeCelles; Giles, 1996) and corresponding tectonic architecture on refraction seismic lines run by Petrobras over the São Francisco Basin and Vazante Group. Note that foreland basin sediments of Bambuí are also strongly affected by thin skinned tectonics. 1 – Espinhaço supergroup/Canastra group, 2 – Paranoá and Macaúbas groups, 3 – Bambuí group, and 4 – Allochthonous units: Vazante, Canastra and Bambuí groups (ROMEIRO-SILVA; ZALÁN, 2007).

Mainly based on reflection seismic, the advancing knowledge of the São Francisco craton and its surrounding fold-and-thrust belts has allowed better stratigraphic correlations between Proterozoic sedimentary megasequences and to devise robust structural frameworks (ALKMIM; MARTINS-NETO, 2012, ROMEIRO-SILVA; ZÁLAN, 2007).

Folds and thrusts developed during the thin-skinned tectonics in the Vazante Group have east vergence direction. Thrust faults are low-angle and dips west at 30° to 35°. There are high-angle reverse faults probably formed because of folding, ancient normal fault reactivations and fault rotation.

Despite its economic relevance, the northern Vazante Group was addressed just by few studies concerning its structural geology. East movement direction of thrust sheets is inferred by sinuous and mostly convex fault traces on map, besides mineral and stretching lineations indicating the same direction of movement. At least two major and progressive deformation events are well recognized in the region: D1 was responsible by isoclinal folding generation and D2 is related to penetrative axial plane cleavage and transverse faults (FREITA SILVA, 1991; PEREIRA, 1994; MARCIA, 2014; CAMPOS NETO, 1984, ROSTIROLLA, 2002). An interesting aspect of the map trace is the Rio Escuro reentrant. This regional syntaxis (concave toward the foreland) basically divides the belt into two sectors (north and south). The arcuate structure may be a result of differential advance of the thrust front over a basement high. Rio Escuro reentrant forms a topographic low covered by recent sediments. Coincidently or not, the reentrant marks profound stratigraphic changes (lacking of Serra do Poço Verde formation to the north of it) and peculiar conditions of ore-forming fluids (occurrence of Zn-silicate ore only to the south of it). Zn-Pb deposits (e.g. Morro Agudo and Vazante mines) are in the maximum advance of the thrust front where sedimentary pile is thicker.

6.2. Faults

Faults at Bonsucesso include: (1) NNW striking reverse fault steeply dipping (60°) to SW, and (2) ESE –WNW and WSW – ENE high-angle transcurrent faults (Figure 10).

The high-angle reverse fault juxtaposed deeper metasedimentary rocks of Serra do Garrote Formation against dolomite rocks of Morro do Calcário Formation. Direction of the movement provided by slickenlines indicates that the fault is reverse (Figure 11). The Zn-Pb sulphide mineralization NNW reverse fault comprises a smoothly curved surface that delineates the occurrence of. Fault-morphology was defined by the limits of fault-core, damage zone and hydrothermal brecciation zone. Slickenlines were measured at fault planes only in phyllite and indicated a transport of top to east (Figure 12). And coupled with slickenline vectors the duplication of carbonate mudstone layers was also a guide to determine the kinematics as reverse. This stratigraphic sequence is neatly repeated by the main thrust fault and it was used as a marker.

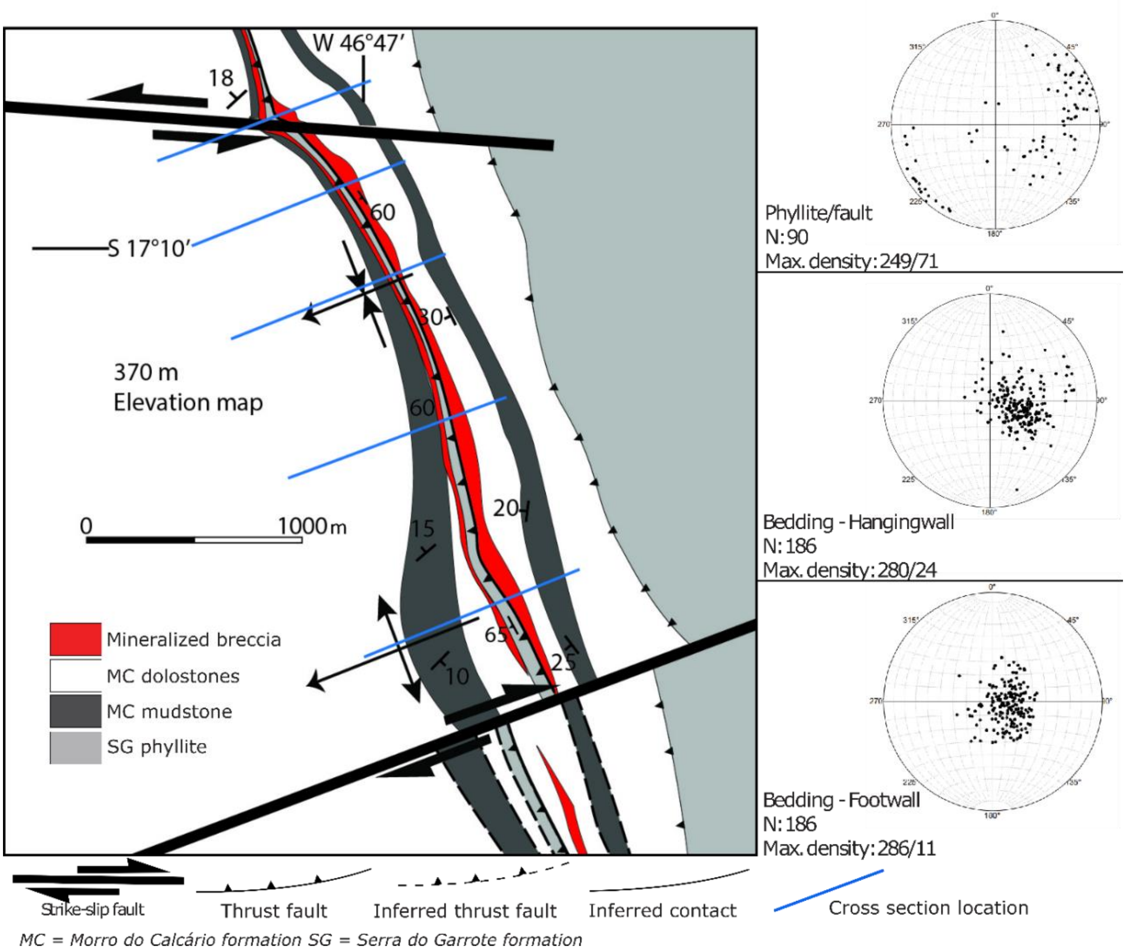


Figure 10: 370 m elevation geologic map showing the mineralized reverse fault truncated by strike-slip faults. At right, lower-hemisphere equal-area stereographic projections of the structures in the Bonsucesso area. “Phyllite/fault” stereonet shows attitude of Serra do Garrote formation rocks emplaced between the two faults blocks.

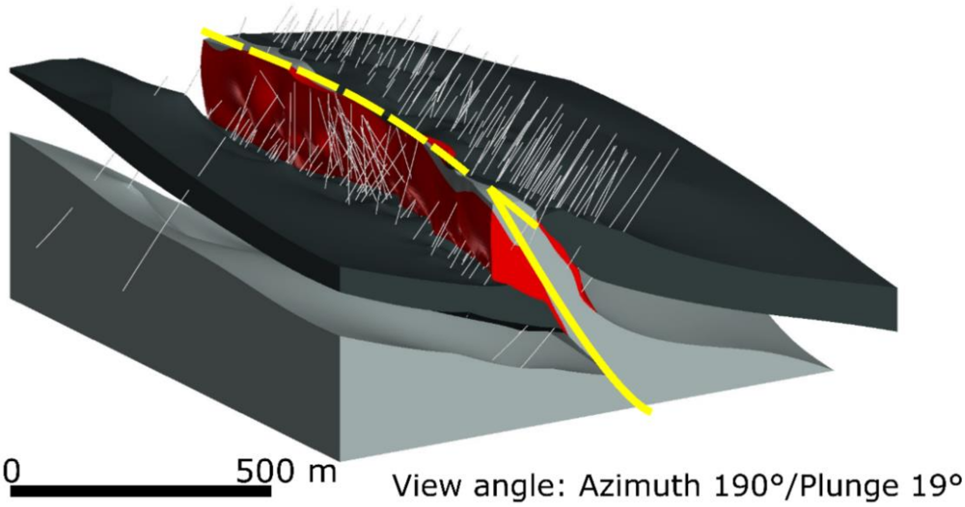


Figure 11: 3-D model of the Bonsucesso reverse fault. Note that the mineralized hydrothermal breccia is segmented by Serra do Garrote formation rocks.

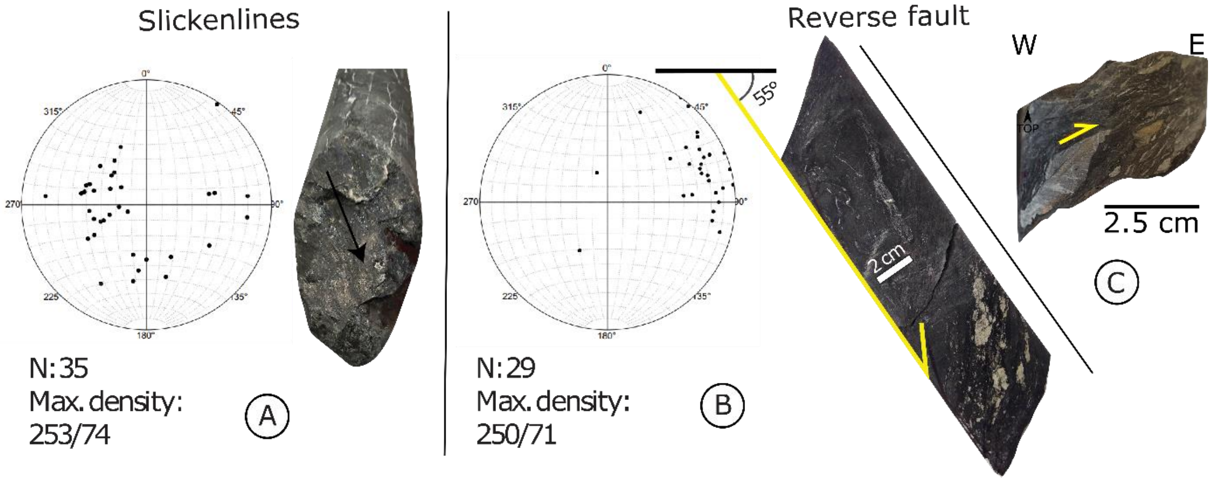


Figure 12: A. Slickenlines observed in reverse faults. B. Reverse fault plain and C. Sigmoid dolomite clast indicates movement to the east.

Using likely displaced mineralized zones (Bonsucesso and Ambrósia deposits) intersected on both sides of these transcurrent faults, offset was estimated to be around 200 meters with a dextral shear sense at the Santa Rita Creek fault (south end of Bonsucesso deposit). At the current northern end of Bonsucesso deposit, the NNW reverse fault is truncated by strike-slip fault and offset to west.

These pairs of faults have a regional expression and their movement direction can be predicted. More field work addressing these faults is fundamental to determine more precisely the kinematics of the strike-slip component and also a normal dip-slip component cannot be ruled out.

6.3. Folds

Anticlines and synclines were defined by measurements of bedding planes at both hanging and footwall blocks. Recrystallization of primary minerals is incipient and bedding is parallel to the first tectonic cleavage (S1). This bedding-parallel foliation is spaced and marked by fine sericite and quartz bands in slates and by sericite, quartz and carbonate clasts in metamudstone. A stylolitic cleavage in the dolomite rocks was not characterized and major bedding-parallel foliation planes were collected at slate/phyllite and carbonate-rich metamudstone layers.

Major folds at Bonsucesso are gently open folds with low-angle axis plunging to southwest. The position of the anticline at the south sector matches the occurrence of thrusted basal rocks of Serra do Garrote formation on shallower levels. At the central sector, the occurrence of phyllites of Serra do Garrote formation is deeper and matches the syncline’s hinge zone (Figure 13).

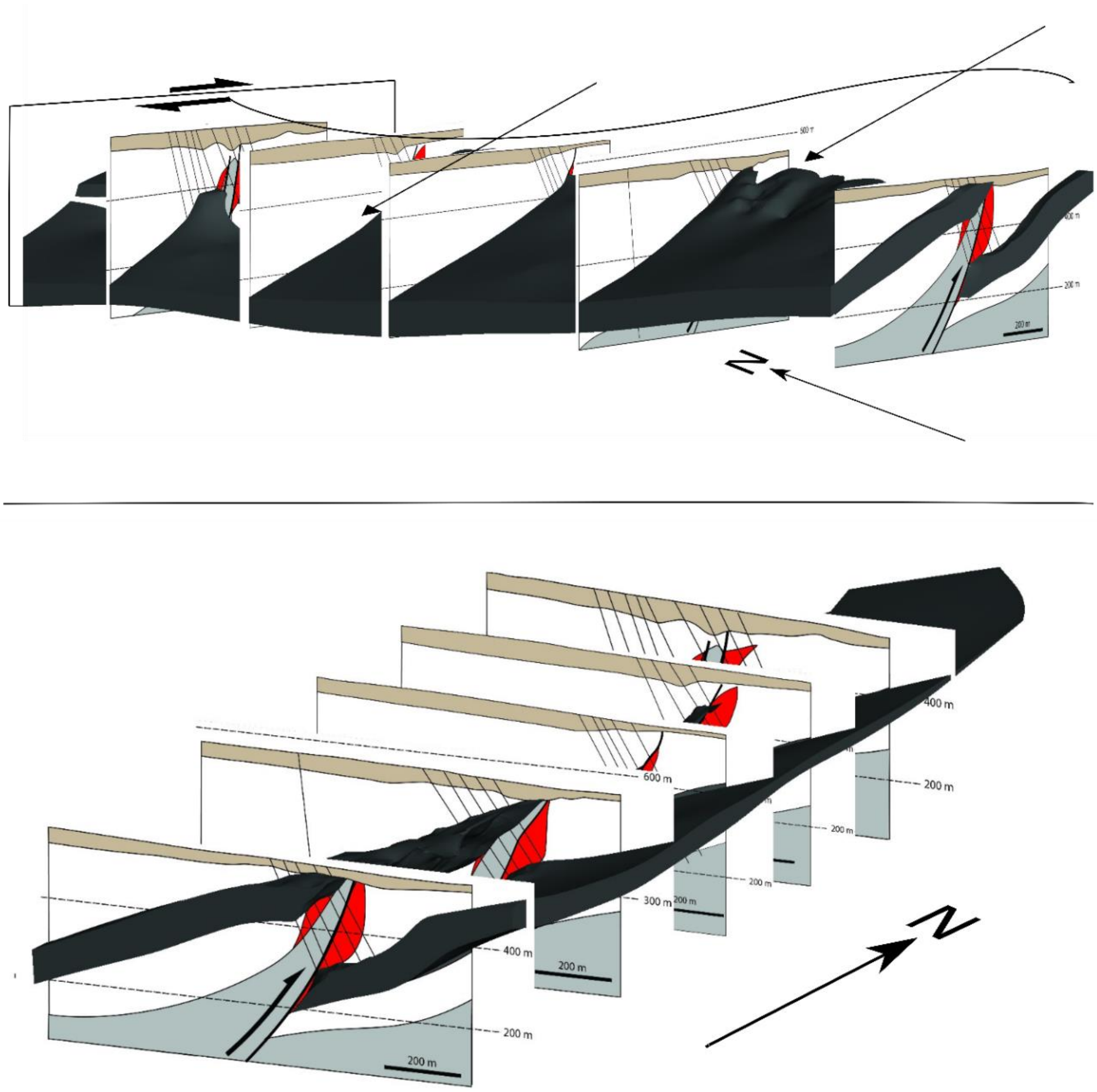


Figure 13: Perspective view of cross sections along Bonsucesso deposit. 3D layers of carbonate mudstone show a clear duplication generated by the reverse fault. Black line above the sections represents the fold traces. Black arrows point down ate the low-angle axis of gently open folds (For legend and cross sections location see geologic map on figure 10).

Isoclinal folds were observed in phyllites of Serra do Garrote formation and comprise a group of centimeter to meter folds characterized by folding of bedding with axis plunging around 10° to and SE or NW. Localized isoclinal folds related to shear zones are also observed (Figure 14:). At Bonsucesso deposit, the axial cleavage parallel to regional isoclinal folds (MONTEIRO et al., 2006) was not recognized.

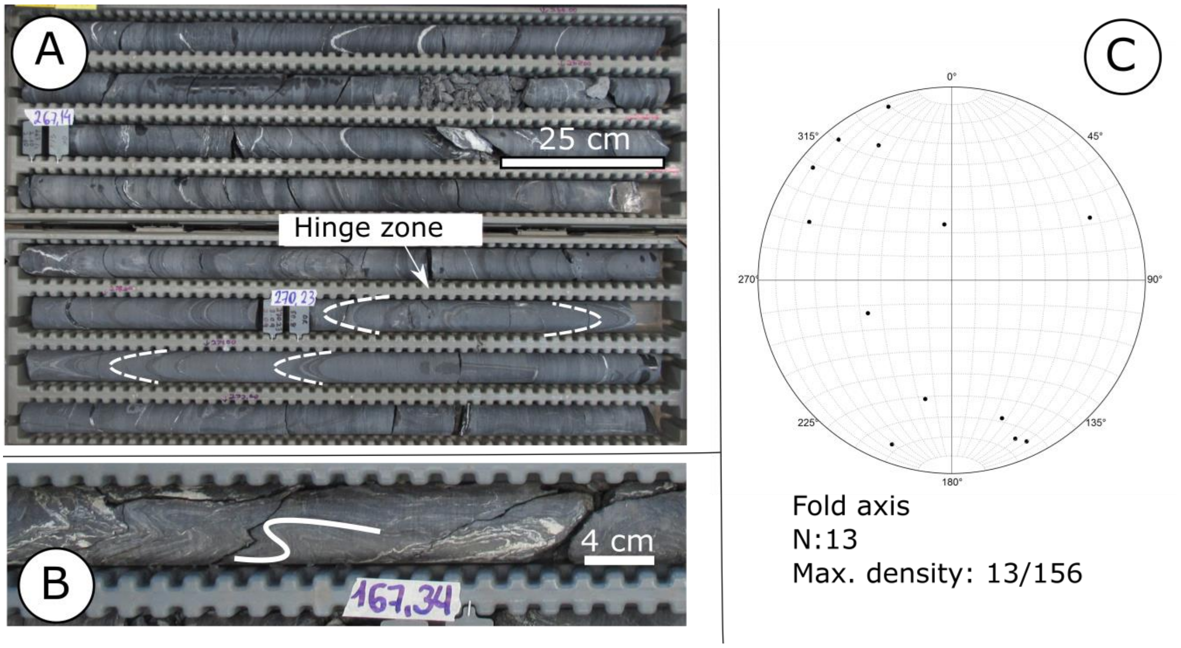


Figure 14: Folds on phyllites of Serra do Garrote Formation inserted between Morro do Calcário faulted blocks. A. Hinge zone of a metric fold. Dashed white lines indicate planes of intersection of bedding surfaces with core samples. Fault-related isoclinal fold within shear zone. C. Low-plunge axis of isoclinal folds.

6.4. Mineralized veins

Mineralization in veins occurs mainly in high-angle veins within the hydrothermal breccia zone. Although they do not correspond to the most volumetrically component of mineralization (i.e., Zn-Pb sulfides filling breccia-matrix), these high-angle veins are mostly extensional veins grown by open-space filling process without shear (Figure 15). There also Sp-bearing veins with lower dips.

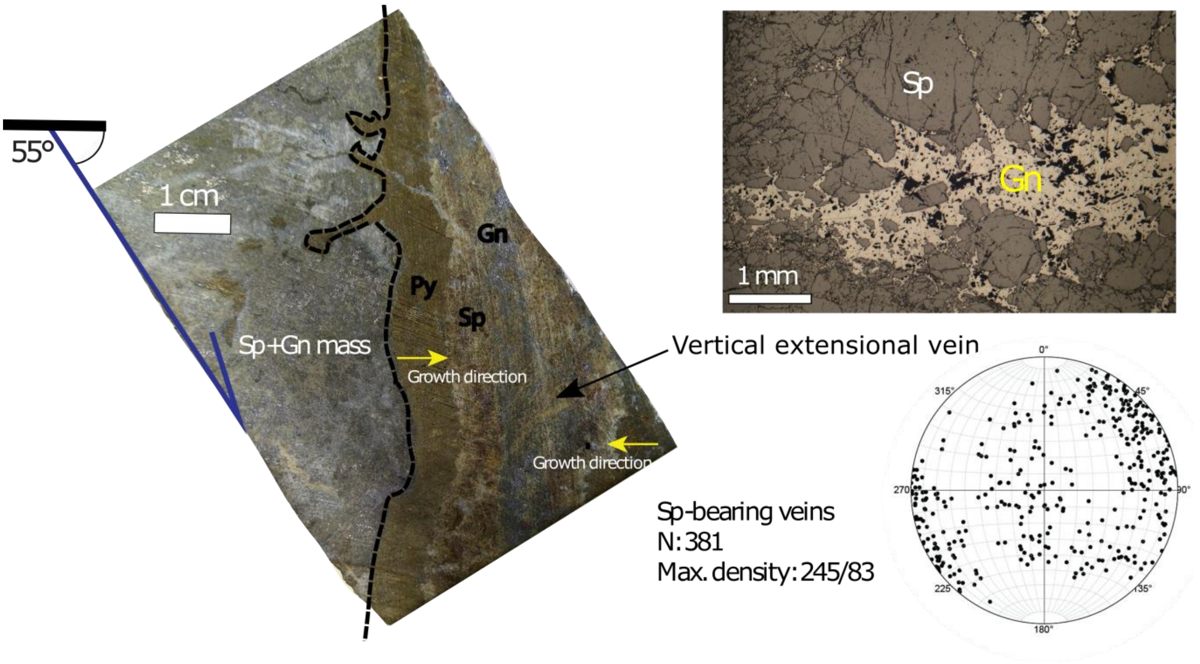


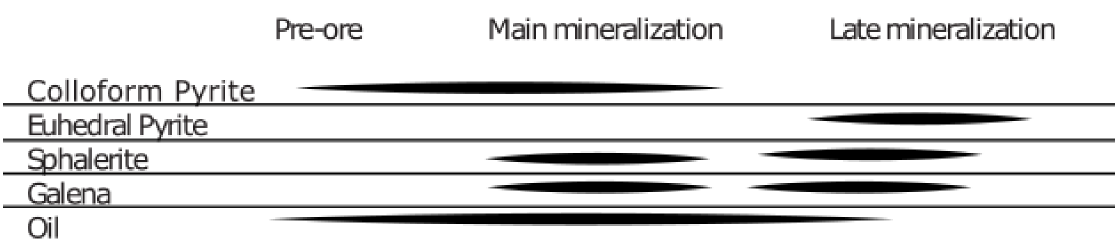
Figure 15: High angle extensional mineralized vein comprised of borders of pyrite (Py) with sphalerite (Sp) and galena (Gn) core. Growth direction is perpendicular to fracture. At the upper right, photograph of Zn and Pb sulfides from vein's core. At this scale it is not possible to distinguish any crystallization order or zonation. And at the lower right corner, lower-hemisphere equal-area stereographic projection of poles of Sp-bearing veins showing at least two major families, they are: (i) high-angles veins and (ii) low to middle dip angle veins. Strike orientation of veins is subparallel to Bonsucesso-fault strike.

7. Discussions

7.1. Paragenetic sequence

The following table summarizes the paragenetic sequence of sulfides at Bonsucesso deposit. As this study was not able to detail the occurrence of phases of quartz, dolomite and other gangue minerals, we assume a widespread distribution of these minerals in all major fluid injection events.

Table 1: Paragenetic sequence of Bonsucesso deposit sulfides:



Paragenetic maps show an iron (Fe) zonation in carbonate minerals with increase towards the center of a sphalerite-bearing vein. For Fe, there is also a slight banding in sphalerite. In regard to manganese (Mn), there is a decrease towards the center of the vein. Cadmium component is strictly related to sphalerite (Sp). And silica (Si) and carbon (C) are concentrated at the core of analyzed vein.

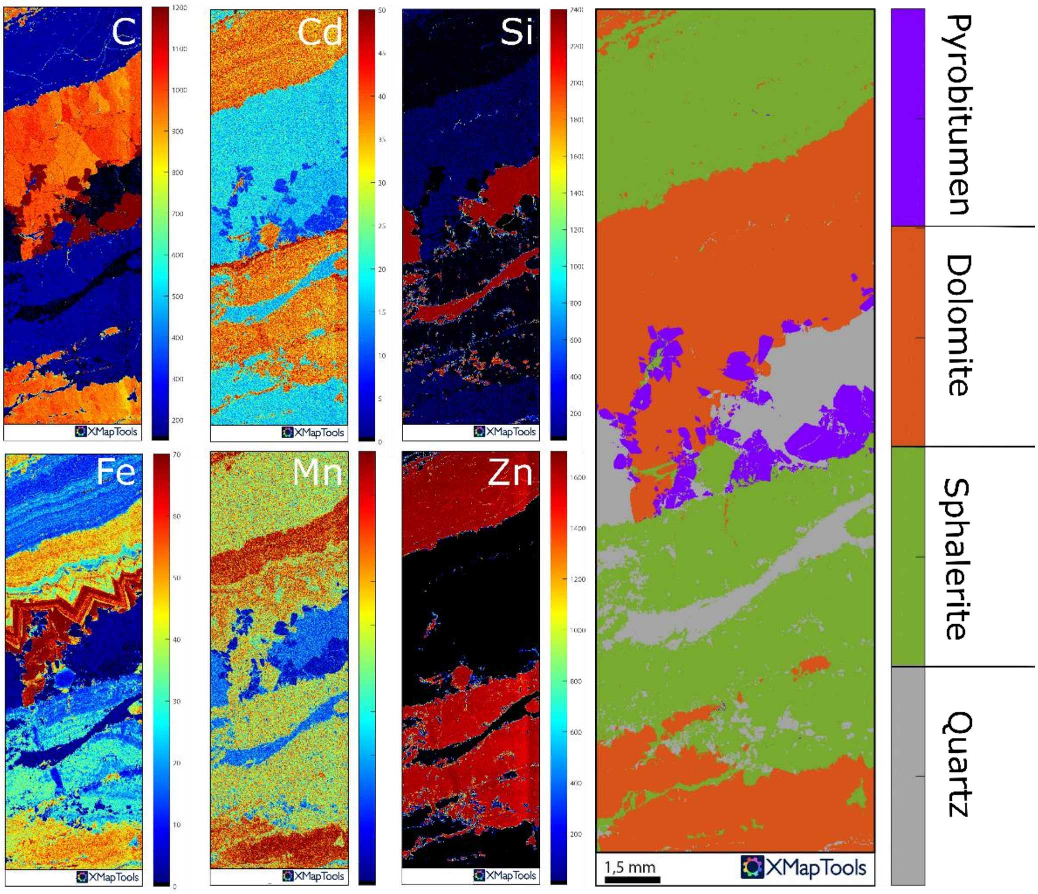


Figure 16: Paragenetic map and compositional maps of an extensional mineralized vein (See location of map on figure 8). C = carbon, Cd = cadmium, Si = silica, Fe = iron, Mn = manganese, Zn = zinc.

7.2. Deformartion history

Sequence of deformation events at Bonsucesso deposit is summarized in the table below:

Table 2: Deformational phases of Bonsucesso deposit.

D0	D1	D2	D3	D4
Bedding	Flexurally induced normal faults	Thrust faults, S1 cleavage, Isoclinal folding with low-plunge to NW and SE	Open folds SW-NE, Strike-slip faults	Late normal faults with small offset (Pinho, 1990; Rostirolla et al. 2002; Cordeiro et al. 2018)
	Main mineralization	*Late mineralization*	*Mineralization is deformed*	
	Local extension/foreland			
Passive margin	***Compressive regime/Brasília Belt thrust front***			

Generation of normal faults with influx of hydrothermal mineralizing fluids occurred in early stages of collision (D1). As the Brasília thrust front advanced (D2), S1 cleavage and isoclinal folding were formed together thrust faults and with subordinate mineralization. Serra do Garrote phyllite was emplaced during this phase. Stage D3 is marked by strong strike-slip component and open-folding. A final extensive regime characterized by normal faults with small displacement or only joints is well recognized regionally (PINHO,1990; ROSTIROLLA et al. 2002, CORDEIRO et al., 2018) but was not described at the scale of Bonsucesso deposit.

Open-folds with SW-NE axis may be contractional fault-related folds resulted of different depths of detachment and displacement transfer with a strike-slip component. These interacting faults (transcurrent and thrust faults) may also control the emergence of deeper layers and segment orebodies.

7.3. Timing of mineralization

The zinc and lead mineralization of Bonsucesso deposit is hosted in a hydrothermal breccia. Development of this breccia is directly linked to the faulting process as the mineralized zone has its geometry defined by it.

The present setting of rocks is the result of a reverse fault that emplaced Serra do Garrote formation phyllites between dolomite rocks of Morro do Calcário formation and generated a stratigraphic duplication attested by the repetition of carbonate mudstone in both fault blocks.

Another important aspect to understand the evolution of the deposit is the absence of shearing between the base of hanging wall-mineralized breccia and top of Serra do Garrote phyllite. Additionally, many drill core intervals show a gradual transition from the dolomite unit to the lower siliciclastic unit. In contrast, the contact between the base of the Serra do Garrote phyllite and the top of the footwall-mineralized breccia exhibits strong shearing with evidences of top-to-east sense of movement.

Regarding the structural evolution of the Bonsucesso deposit, three different scenarios are suggested for the formation of the Pb-Zn mineralization: i) mineralization was formed during local extensional regime before or while basin inversion completion, ii) Bonsucesso mineralization was generated during a local and regional compressive state regime during basin inversion. Its high angle fault is the result of reactivation of inherited normal faults. Phyllite between faults blocks is the result of progressive advance of the thrust front, iii) controlling structures and mineralization were formed during local and regional compression regime. Bonsucesso high-angle fault was primarily low-angle and then rotated to the current position.

7.3.1. Scenario 1

Elements to support this hypothesis:

- High-angle of the controlling fault;
- High-angle of mineralized veins;
- High-angle extensional mineralized veins with zero shear;
- Normal faults are efficient conduits for hydrothermal flux (SIBSON, 2000) and in many cases form barriers for hydrocarbon accumulations (HARDMAN; BOOTH, 1991).
- Disposition of mineralized breccias into two segments divided by an allochthonous phyllite. Emplacement of Serra do Garrote formation rocks between carbonate rocks of Morro do Calcário occurred after main mineralization process, once the latter are deformed by the former.

Elements to argue against this hypothesis:

- Which major regional extensional event would be responsible by mineralization before the complete inversion? Layers in both fault blocks show little thickness alteration, whether an association with normal faults related to Vazante Group deposition is brought up. Therefore, it had been an extension after Vazante Group deposition. However, a major event capable of such extension prior to the completion of basin inversion is the syn-orogenic formation of the foreland basin hosting Bambuí Group sediments (BRITO NEVES et al., 1996, ALMEIDA et al., 2000, ALKMIM, 2004, REIS; ALKMIM, 2015). And far-reaching normal faulting is described by REIS et al. (2017) as the result of a forebulge uplift in the east. But effects of this process over Vazante Group rocks are still unclear. Also, as the Vazante Group the Bambuí sediments were also affected by thin- skinned tectonics and large thrust faults are traceable along the foreland sedimentary sequence (REIS; SUSS, 2016, REIS et al., 2017).

7.3.2. Scenario 2

Elements to support this hypothesis:

- Equally to the previous hypothesis, fault promoted the increase of rock permeability in the damage zone and connected overpressured fluids of sealed reservoirs. Then fluids migrated to precipitation site where geochemical conditions were favorable.
- Inversion of inherited normal faults is normally evoked to explain the formation of some mineral deposits controlled by high angle reverse faults as described by Sibson's model of fault-valve (SIBSON, 1988). Because under compressional conditions (horizontal sigma 1), development of high-angle thrust faults is not favorable. And for theses reactivations to take place fluid pressure must exceed the lithostatic load. So, huge amounts of overpressured fluids accumulated below are suddenly discharged to high structural levels when this limit is reached. And this cycle may be repeated multiple times as hydrothermal mineralizing fluids may seal the cracks pushing the pressure to build up once again.

Elements to argue against this hypothesis:

- The high-angle fault itself is an issue in the same way that the high-angle extensional veins are.
- Mineralizing fault-valve process is well-known in orogenic gold deposits and controlling high-angle fault show deep roots reaching the seismogenic crustal limit (SIBSON, 1988). There is no evidence yet that Bonsucesso fault or any thrust fault in Vazante Belt have such deep extensions.

7.3.3. Scenario 3

Elements to support this hypothesis:

- The mineralized zones are controlled by a reverse fault.
- High-angle of controlling fault may be a rotation caused by absorption of regional shortening.

Elements to argue against this hypothesis:

- Low-angle thrust faults are not commonly associated with high dilation zones.
- Mineralized veins have no shear at Bonsucesso deposit. Even if veins and fault planes are back-rotated to a position close to a common low-angle thrust fault, mean veining atitude does not fit into expected riedel-shear fractures.

7.4. Bonsucesso deposit x Vazante Belt deposits

The current biggest base-metal deposits of Vazante Belt are Morro Agudo (Zn-Pb sulfide deposit with 20 Mt @ 5.0% Zn and 1.75% Pb) and Vazante (world's largest hypogene non-sulfide Zn deposit with 60 Mt @ 20% Zn, including willemite-ore and supergenic-ore).

Vazante Group deposits occur in carbonate host rocks close to the margin of an uplifted foreland basin and their Zn-Pb ore-minerals contain saline fluid inclusions, both features suggest genetics similarities to Mississippi Valley-type deposits (APPOLD; MONTEIRO, 2009). These deposits hosted in carbonate-dominated sequences formed from basinal brines expelled as a result of tectonic activity (LEACH et al., 2010). However, the hypogene Zn silicate of Vazante deposit differs significantly from this model regarding to ore-type and homogenization temperature (MONTEIRO et al., 1999; APPOLD; MONTEIRO, 2009).

Morro Agudo deposit is hosted mainly in a doloarenite layer whose matrix was replaced by sphalerite with subordinate mineralization in fault-dolomite breccia, intraformational dolomite breccia and also replaced stratiform orebodies in carbonate lenses within metapelites of Serra da Lapa formation (CORDEIRO et al., 2018).

Mineralization in the Morro Agudo deposit is interpreted to be related with fluids ascending from a main normal fault located in the east limit of the deposit (CUNHA et al., 2007, 2000 DARDENNE; FREITAS-SILVA, 1999, MISI et al., 2005, 1999). Likewise, Cunha et al. (2000) and Misi et al. (2005) showed a cooling pattern in homogenization temperature, salinity and isotopic data towards deeper and distal sectors from the main fault. Nonetheless, there is a set of smaller normal faults with an oblique component that offset the orebodies and host rocks (CORDEIRO et al. 2018). These faults are ore modifiers and have the same attitude of the main fault and also the main fault does not feature any clue of hydrothermal alteration expected to a feeder zone. Therefore, the referred structure would be only other later but larger normal fault modifying the whole rock sequence (CORDEIRO et al., 2018). So, without contradicting the recognized cooling pattern, Cordeiro et al. (2018) call for any conduit capable of mobilize fluids before faulting into smaller blocks and that a major feeder may have been eroded or simply not intersected by drilling yet. Hence mineralization at Morro Agudo deposit took place before basin inversion.

In this sense, even if Morro Agudo had multiple phases of ore fluids injection, they all point to an early bulk mineralization event happened before overprinting of compressive structures and may be contemporaneous with a hypothesis of pre-thrust mineralization of Bonsucesso. Also, Cordeiro et al. (2018) discussed that there is a strong although overlooked strike-slip component in Morro Agudo, possibly related to the collisions between Amazonian, São Francisco and Paranapanema paleoplates (BRITO NEVES; FUCK, 2013).

The Ambrósia, Ambrósia Sul and Bonsucesso deposits form an aligned cluster of Zn-Pb mineralization (Figure 17) with minor offset by strike-slip fault and may constitute an earlier permeable normal fault system with high influx of hydrothermal fluids later overprinted by thrusting.

Ambrósia Sul deposit represents another Zn-Pb sulfide deposit formed during an early extensional event and is located in the same trend 5 kilometers southwards from Bonsucesso (merece uma imagem simples). According to Neto (2019), mineralization is associated with a syn-orogenic extension during formation of Bambuí Group foreland basin and normal faulting is related to forebulge uplift (REIS et al., 2017). Although the emergence of basal layers in the Ambrósia Sul deposit is not so evident as in Bonsucesso deposit, Neto (2019) interpreted the mineralized veins formed during a compressive regime high-angle,cut by late low-angle thrust faults associated with minor sphalerite-bearing veins.

The Ambrósia Sul deposit is the south extension of the long-known Ambrósia Zn-Pb deposit whose formation is associated with epigenetic processes (MONTEIRO et al. 2006) and is also controlled by a high-angle fault. This deposit is located just 1.5 kilometers to south from Bonsucesso and its mineralization style (MONTEIRO et al. 2006, 2007) is similar to Bonsucesso. These deposits are separated by a transcurrent fault zone and projection of their mineralization onto surface show a 200 meters relative off-set if it is assumed that they are controlled by the same fault.

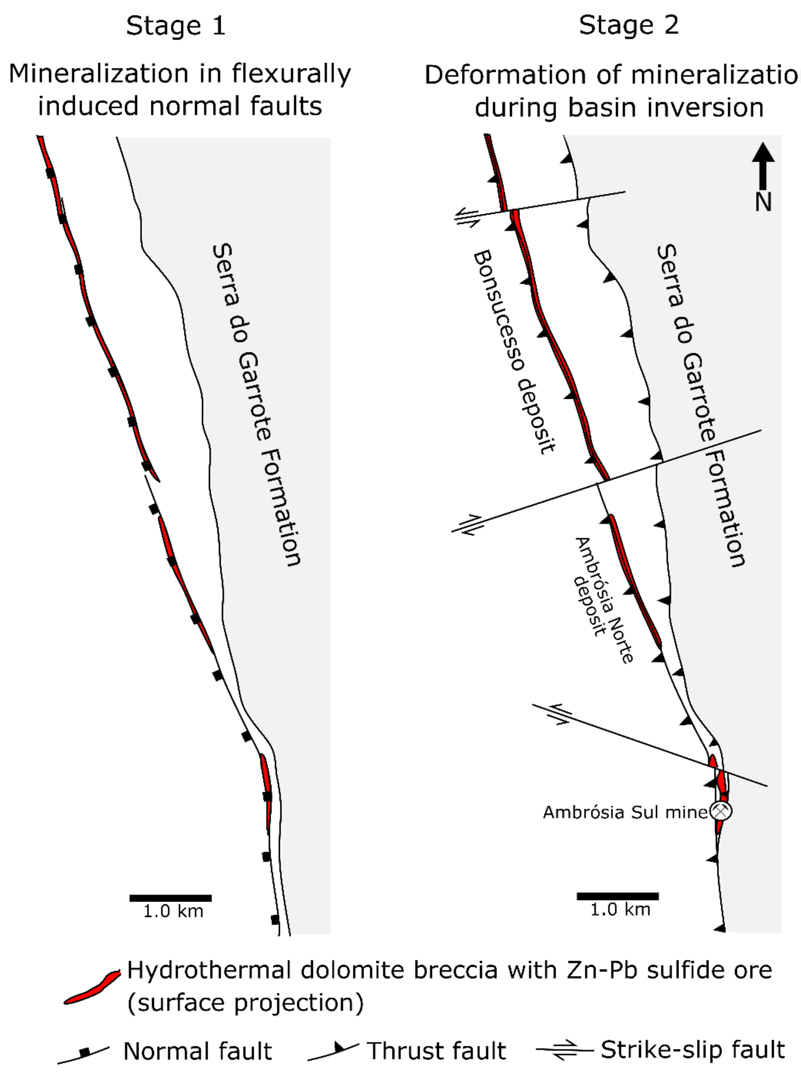


Figure 17: Simplified genetic model of mineralization-related structures at Bonsucesso, Ambrósia and Ambrosia Sul deposits. Stage 1: Extensional fault system took place and formed the bulk mineraization of all three deposits. Stage II: Advance of thrust front took over ancient extensive structures; formation of reverse faults; strike-slip displacements.

The mineralization of Vazante non-sulfide Zn deposit is controlled by a 12 kilometers long fault zone trending northeast and dipping 60° to northwest (MONTEIRO et al. 2017). This major shear zone also shows a complex deformation history (ROSTIROLLA et al., 2002; PINNHO, 1990; DARDENNE, 1974) and ian important role in the mineralization process as the main conduit, besides the many particular features involving willemite formation and hydrothermal alteration processes unequal in the world (MONTEIRO et al., 1999).

7.5. Bonsucesso deposit x Tectonic settings of MVT Pb-Zn deposits on Earth history

As discussed by Leach et al. (2010), the tectonic setting of ore deposits is the conjuncture where they are formed and eventually destroyed. And this moment on an evolving Earth "determines the host-rock type, ore controls, temperature, and pressure of the depositional processes, as well as the survivability of the deposit during tectonic recycling" (Leach et al., 2010).

Accordingly to Bradley and Leach (2003), the most suitable environments for MVT mineralization are former passive margin platform carbonates that ended up beneath foreland basin deposits generated during the collisional orogeny. After orogeny has ceased a hydrologic flux of basinal brines would be favorable and percolate through normal faults induced by crustal flexure occurred during the formation of accommodation space of the foreland basin (Leach et al., 2010).

The way that Bonsucesso's mineralization fit in this model is that it is (i) hosted in former passive margin platform carbonates beneath a foreland basin, (ii) is controlled by high-angle dilational structure, and (iii) salinity, isotopic and homogenization temperatures of near-by deposits have upper crustal/basinal signature (MONTEIRO et al., 2006, 2007). Although, Vazante Group has undergone a shortening process that lasted longer than the foreland basin deposition process and the latter was also involved in the thin-skinned tectonics as it was added to external domains of Brasília Belt during the late stages of assembly of West Gondwana (REIS; ALKMIM, 2015; ALKMIM, 2004; ALKMIM et al., 1996, 2001; BRITO-NEVES, 2004; BRITO-NEVES et al., 1999; CAXITO et al., 2014; PEDROSA-SOARES et al., 2001, 2007; VALERIANO et al., 2004). Finally, an extensional phase of mineralization before basin inversion with some late remobilization also agrees with Misi et al. (2014, 2005, 1999), Monteiro et al. (2006, 2007), Cunha et al. (2007, 2000); Dardenne and Freitas-Silva (1999) proposals for Morro Agudo, Ambrosia, Fagundes and Vazante deposits.

7.6. Implications for mineral exploration

Zn-Pb deposits in Vazante belt are intimately linked to fault zones. Flow of metal-rich fluids occurred throughout the basin and dilational structures functioned as avenues for them to be redistributed along strike and crystallize where chemical conditions were adequate. Contrasting rheological properties of brittle dolomite rocks and more ductile phyllites transformed Vazante Group in a giant fluid trap where permeability in carbonate rocks was constantly increased by faulting and different reservoirs were allowed to interact.

Historically mineral exploration programs evolved through follow up of outstanding geochemical anomalies (e.g. metal rich gossan). At Paracatu and Vazante region it was not any different, all major orebodies current mined were once cropping out. In the entire region, Bonsucesso deposit is the first orebody discovered lying under a 30 meter thick pile of recent sediments. Although, its discovery is particularly connected with a gossan 1 km to south slightly with the same strike (North Ambrósia) and targeted for decades.

Our model present a likely set of regional proportions involving flexurally-induced normal faults later affected by thrust and strike-slip faults. High-angle reverse structures as the Bonsucesso fault may suggest a direct link of mineralization with compressive regime, but early extensional features related to main stage of Zn-Pb sulfide formation are identified and better fit the general model proposed for most of Vazante belt deposits of bulk mineralization pre-inversion (MISI et al. 2014, 2005; MONTEIRO et al., 2006, 2007).

High-angle fault-zones dipping to west (general dip of the thrust belt) may be mistaken as originally thrust-faults and disguise other exploration opportunities such as their likely own antithetic pair. Regarding to that, normal antithetic faults controlling mineralization are already known in the Ambrósia Sul deposit (NETO, 2019) and poorly explored along the Vazante Belt. In addition to that, current strike-slip faults also might have worked as transfer faults during extension phase and flipped their dip as it is documented in many extension sets around the world (MILANI; DAVISON, 1988; CHOROWICZ, 1989). Therefore, these possibilities should be taken into account when exploring in regions of interacting faults.

8. Conclusions

- Mineralization was likely formed in an extensional regime setting in breccia zones controlled by flexurally-induced normal faults
- Current Zn-Pb sulfide ore is hosted in a hydrothermal dolomitic breccia controlled by a high-angle reverse fault striking N20W and dipping 60° to SW.
- Mineralization is hosted mainly in the breccia-matrix, but mineralization is also hosted in high-angle extensional veins
- Slickenlines indicate a transport of top to East in a thrust system with detachment zone in phyllites of Serra do Garrote Formation
- Phosphate-bearing carbonate mudstone layer was duplicated by the reverse fault
- Strike-slip faults offset the mineralization zones and host rocks
- Search for mineralizaton extensions controlled by faults should take into account an early normal faulting setting deformed by basin inversion.

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CAPÍTULO 3

O depósito de Zn e Pb de Bonsucesso está hospedado em rochas do Grupo Vazante de idade Mesoproterozoica. Diferentemente do atual maior depósito de Zn e Pb em sulfetos da região, o majoritariamente estratiforme Morro Agudo, este recém descoberto depósito é controlado por uma falha reversa de alto ângulo com direção N20W e mergulho de 60° para SW. Os corpos de minério estão em zona de brecha dolomítica hidrotermal paralela à falha desenvolvida em rochas dolomíticas da Formação Morro do Calcário. A formação do maior volume de mineralização deve ter se dado em regime extensional controlado por falha normal. O avanço dos empurrões da frente orogênica do Cinturão Brasília promoveu a sobreposição destas estruturas extensionais. Estrias de falha, degraus de falha e também outros indicadores cinemáticos como sigmoides indicam transporte tectônico de topo para leste na zona de falha mineralizada. A unidade imediatamente abaixo (filitos carbonosos da Formação Serra do Garrote) atuou como zona de descolamento basal, emergiu nas zonas de falha e faz contato por falha com os carbonatos na zona mineralizada. Há um componente transcorrente com forte expressão regional na forma de grandes pares conjugados de falhas. Estas falhas transcorrentes deformaram as encaixantes e a mineralização do depósito de Bonsucesso.O motor da circulação dos fluidos bacinais foi a tectônica compressiva sobre a paleoplaca do São Franscisco durante a orogenia Brasiliana. As zonas de falha atuaram como condutos e também como armadilhas dos fluidos. A fase extensional inicial sobre sedimentos de uma margem passiva antiga (i.e., Grupo Vazante) deve estar associada com o desenvolvimento da bacia de ante-país onde os sedimentos do Grupo Bambuí foram depositados.

Ao estudar os controles do depósito de Bonsucesso ficou evidenciada a atuação dos filitos basais como zona de descolamento e seu alçamento nas zonas de falha. Até o momento, esta geometria ainda não havia sido descrita na região estudada, embora fosse esperada, uma vez que se trata de um antigo cinturão de dobras e empurrões e o contraste reológico entre dolomitos e filitos normalmente produziria feições como esta. Este antigo sistema extensivo, agora invertido, sugere uma conexão genética entre os depósitos de Ambrósia, Ambrósia Sul e Bonsucesso e tem implicações diretas na pesquisa mineral, pois o mesmo processo gerador deve ter se repetido nas extensões imediatas dos depósitos conhecidos e em suas proximidades. Falhas transcorrentes podem ter atuado como falhas de transferência durante a fase de extensão e podem ter invertido o caimento das falhas controladoras de mineralizações.